PYROMETERS

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RECENT DEVELOPMENTS IN PYROMETRIC APPLIANCES AND METHODS FOR CALIBRATING TEMPERATURE MEASURING INSTRUMENTS

WITH NOTES ON ELECTRIC FURNACES

BY

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PREFACE

THE aim of this small book is to deal briefly with recent developments in pyrometric appliances and to indicate the methods in use for calibrating temperature-measuring instruments.

It is hoped that it may serve as a connecting link between the textbooks on heat on the one hand and the advanced treatises on pyrometry on the other. Hence the writer has adopted the plan of inserting at the beginning of each chapter references to particular sections of standard textbooks on physics where the introductory matter may be found, and a list of published reports and treatises on pyrometry is given in the appendix.

In selecting instruments for description in these pages attention has been given to outfits designed to meet novel requirements, in the hope that such instruments will suggest to the reader a solution of the particular problems with which he has to contend.

It is, of course, assumed that the reader has access to the catalogues of the manufacturers of thermometers and pyrometers, so detailed accounts of the many forms of total radiation and thermo-electric pyrometers have been omitted.

It has been thought fit to confine the discussion of optical pyrometry to one type of instrument, and that the simplest mechanically, for it is really astonishing to find what a high degree of accuracy can be attained with the disappearing filament type of pyrometer when used with due care.

It is a pleasure to record the courtesy of the many people who have given permission to reproduce diagrams and material published in reports or journals for which they are responsible.

The author's especial thanks are due to the following:

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Mr. Lawson of Siemens Bros., Woolwich.

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CHAPTER I

TEMPERATURE SCALES

INTRODUCTORY matter on the gas thermometer and the realization of the working scale will be found in the following: Edser's *Heat*, pp. 106 to 112; Watson's *Textbook of Physics*, p. 221; Duncan and Starling's *Physics*, p. 408; Watson's *Intermediate Physics*, p. 144; Griffiths' *Methods of Measuring Temperature*, Chap. I.

IN industrial operations temperatures are measured ranging from − 200° C. to + 3,000° C., and necessarily many diverse types of instruments have to be employed. Hence it is a matter of paramount importance that all temperature-measuring appliances should be based on a consistent scale of temperature.

The standard scale of temperature universally accepted at the present time has been arrived at by a process of gradual evolution.

One's ideas of temperature measurements are inseparably associated with the mercury thermometer and the notion is common that the mercury thermometer is a fundamental standard. Up to forty years ago it was certainly the most convenient means of obtaining a practical scale over the limited range in which it was usable. Nowadays it is accepted as being merely an empirical instrument, for it has been demonstrated that a scale based on a gas thermometer, using a stable gas such as

nitrogen, possesses great advantages in range and independence of the intrinsic properties of the envelope.

Lord Kelvin, by an ingenious piece of theoretical reasoning, based on the laws of thermodynamics, showed how it was possible to define a scale of temperature which would be independent of the properties of any particular substance, and that this thermodynamical scale could be realized from the scale given by a gas thermometer, if by subsidiary experiments certain small corrections were obtained.

Later researches have connected up the Kelvin scale with the heat and light emission from hot bodies. This has rendered practicable the measurement of the temperature of hot bodies from their heat emission.

Thus all temperature measurements can be referred to the one basic scale, and it is immaterial whether the observations are made with a resistance or a helium thermometer at low temperatures; with a mercury thermometer at ordinary temperatures; with a thermo-element at higher temperatures; or with a total radiation or optical pyrometer, at the highest temperatures; they will all give identical values over the range they overlap.

It might be appropriate to quote here the specification of the temperature scale given in the test pamphlet of the Physics Department of the National Physical Laboratory—

The "International" Temperature Scale.

Immediately prior to the war an attempt was made to arrive at international agreement as to the adoption of a standard or fundamental temperature scale by the three national standardizing laboratories—the National Physical Laboratory, the Bureau of Standards, Washington, and the Reichsanstalt. The outbreak

of war prevented formal acceptance of the centigrade thermodynamic scale as the "*international*" *scale of temperature*. This scale has been adopted in the meantime at the National Physical Laboratory.

Lord Kelvin showed long ago the theoretical advantages of the thermodynamic (or absolute) scale, and that a perfect gas (i.e. one which obeys Boyle's law and suffers no temperature change when subjected to free expansion with no external work) would give a scale identical with the thermodynamic. The practical advantage of the thermodynamic scale is that the high temperature scale evaluated on the basis of the laws of radiation is consistent with that of the gas thermometer at lower temperatures.

To promote the general use of the same temperature scale in both scientific and industrial circles, the following alternative methods have been agreed as a means of attaining a "*practical scale*" of temperature which approximates to the thermodynamic scale. A statement of the exact relationship between the two scales is deferred until a sufficient degree of concordance has been reached in the measurements. There is, however, every reason to believe that the practical scale over the range 0° to 100° C. agrees within the limits of experimental error with the hydrogen scale of the International Bureau of Weights and Measures.

(*a*) *The Hydrogen Scale*. In the interval between 0° and 100° C. the practical scale is realized with the exactness required for work of the highest precision in the scale of the constant-volume hydrogen thermometer, having for fixed points the temperature of pure ice melting under normal atmospheric pressure (0° C.) and that of the vapour of distilled water in ebullition under normal atmospheric pressure (100° C.).

(*b*) *The Platinum-resistance Thermometer Scale*. In the interval between the freezing point of mercury and the boiling point of sulphur the practical scale is realized with sufficient exactness by the platinum-resistance thermometer standardized at the temperatures of melting ice (0° C.), of the vapour of water boiling under normal atmospheric pressure (100° C.), and of the vapour of sulphur boiling under normal atmospheric pressure in a specified form of apparatus and under specified conditions. The temperature of the vapour under these conditions is to be taken as 444·5° C. The temperature t on the international scale is deduced from the resistance of the platinum thermometer by the formula—

$$t - t_{pt} = \delta\left[\left(\frac{t}{100}\right)^2 - \frac{t}{100}\right] = \delta\, t\,(t - 100)\, 10^{-4}$$

where $t_{pt} = 100 \times (R - R_0)/(R_{100} - R_0)$, and R, R_0 and R_{100} are the observed resistances of the thermometer at temperatures $t°$, 0° and 100° respectively. The platinum of which the

thermometer is made shall be of such a degree of purity that the value of δ in this equation shall not be greater than 1·52, and R_{100}/R_0 shall not be less than 1·386.

The boiling point of sulphur t_s at pressure p millimetres is connected with that at standard pressure, 760 millimetres, by the formula—

$$t = 444{\cdot}5 + 0{\cdot}0908\,(p - 760) - 0{\cdot}000047\,(p - 760)^2$$

(c) *The Fixed Point Scale.* The practical scale is also realized with sufficient exactness by the use of the following fixed points, in addition to the three fundamental points above specified—

	Temperature on the Centigrade Thermodynamic Scale.
Boiling point of oxygen	$182{\cdot}9^\circ_5 + 0{\cdot}01258^\circ\,(p - 760) - 0{\cdot}0000079^\circ\,(p - 760)^2$
,, ,, ,, carbon dioxide	$78{\cdot}5^\circ + 0{\cdot}01595^\circ\,(p - 760) - 0{\cdot}0000111^\circ\,(p - 760)^2$
Freezing point of mercury	$-38{\cdot}88^\circ$
Transformation point of sodium sulphate	$32{\cdot}38^\circ$
Boiling point of naphthalene	$217{\cdot}9^\circ + 0{\cdot}058\,(p - 760)$
,, ,, ,, benzophenone (pure)	$305{\cdot}9^\circ + 0{\cdot}063\,(p - 760)$
Melting or freezing point of—	
Antimony	630°
Silver (in a reducing atmosphere) . .	961°
Gold	1,063°
Copper (in a reducing atmosphere) . .	1,083°

Fixed points of the second order are provided by the melting or freezing points of—

Tin	231·8°
Cadmium	320·9°
Zinc	419·4°
Common salt (pure) . .	801°

CHAPTER II

EXPANSION THERMOMETERS AND THEIR CALIBRATION

Mercury-in-Glass Thermometers.

THE outstanding member of this class is the mercury-in-glass thermometer. The amount of thought and ingenuity which has been expended on the development of this instrument is truly stupendous, and as the result of it, a well made mercury thermometer with a range from 0° to 100° C. should read correctly at all points of the scale to within 0·05° C.*

When borosilicate glass is employed in the construction, and the space above the mercury column filled with nitrogen under a pressure of about 15 atmospheres, the range of the mercury thermometer can be extended up to 450° C. It must, however, be realized that these temperatures impose a severe strain on the instrument, and exposure to the higher temperatures for even a moderate length of time results in a change of zero of the instrument, which, in a well-annealed instrument, may not amount to more than $\frac{1}{5}$° C.

There is no doubt that these temporary changes of zero would be considerably reduced if it were possible to employ fused silica instead of borosilicate glass for the envelope ; but up to the present

* Calorimetric thermometers with a range of 13° to 20° C. and subdivided to 0·01° C. can be obtained with a correction at no part of the scale exceeding 0·01° apart from zero error, which is immaterial when temperature differences only are to be measured.

the practical difficulties attendant on the working of silica and the marking of the graduations have limited the utilization of this material.

Calibration of Mercury Thermometers.

The old method of obtaining corrections to the readings of a mercury thermometer by a point by point calibration of the bore of the capillary, and the determination of the ice and steam points, is now obsolete. The mercury thermometer is a purely empirical instrument and the errors of a particular instrument can best be obtained by direct comparison with a standard. This is the practice adopted in all national standardizing laboratories at the present day.

The master standards are a series of thermometers whose scales have been obtained by the procedure indicated in Chapter I under the heading: "The International Temperature Scale."

Determination of the Zero of a Thermometer.

Whatever range of temperature the thermometer is designed to measure the scale should always include the 0° C. point, as then it will be possible to keep a check on the permanency of the calibration of observations taken in melting ice.

In the best class of instrument, a short length of the scale round about 0° C. is engraved, and, if necessary, the expansion of the mercury between this temperature and the commencement of the working range is taken up by a small subsidiary bulb. In taking the ice point, the thermometer should be immersed in fine ice shavings, moistened with distilled water, with the top of the column showing.

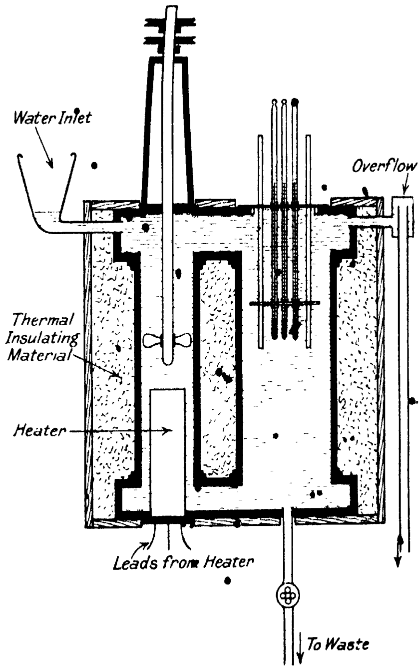


FIG. 1.
WATER BATH FOR COMPARISON OF THERMOMETERS BETWEEN 0° C. AND 100° C.

Comparison with a Standard between 0° and 100° C.

These comparisons are effected in a well stirred water-bath, constructed as shown in Fig. 1. It consists of two vertical tubes cross-connected at their upper and lower ends so as to afford a circuit for the water.

The circulation of the water is produced by a propeller working in the left-hand tube. At the bottom of this tube are situated the electric heaters, the thermometers being situated in the larger tube.

The heaters are made by winding nichrome tape on mica strips, which are made a tight fit in thin copper envelopes projecting up into the tube; their open ends being soldered into the base of the tube.

By keeping the thermal capacity of the heaters small, it is possible to obtain very quick response to the current regulator; so that when the temperature of the bath has very nearly reached the point at which an intercomparison of the thermometers is desired, all that is necessary is to cut down the energy supply to the extent that will just suffice to produce a very small rising temperature. The conditions become sufficiently settled for a set of observations to be taken in about a minute from the instant of cutting down the electrical supply.

Comparison with a Standard over the range of 100° to 200° C.

In principle, the baths employed for this range are similar to the water-baths, but cotton-seed oil is employed instead of water, and gas heating is substituted for electrical heating.

The bath is contained in an enclosure of the form shown in Fig. 2, which represents a molten salt bath, described later.

The limb containing the thermometers is lightly insulated with a layer of asbestos cord to prevent hot spots.

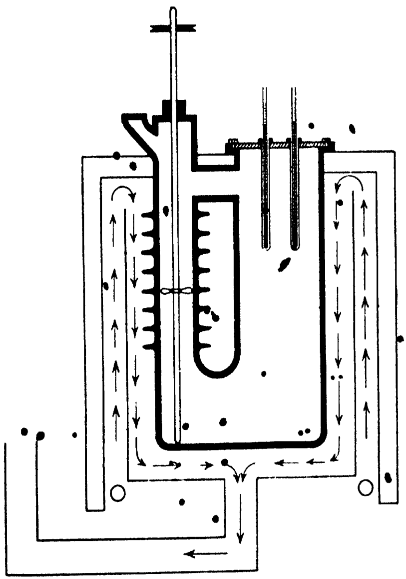


FIG. 2.
MOLTEN-SALT BATH FOR COMPARISON OF THERMOMETERS BETWEEN 200° C. AND 450° C.

To obtain full immersion of the thermometers, it is necessary to maintain the oil level up to the plate carrying the thermometers, and the expansion of the

oil with increasing temperature is allowed for by the introduction of an overflow pipe at this level. Comparison of thermometers can be carried out most conveniently at successively higher temperatures, as then it is only necessary to fill the bath at the lowest temperature, and let the overflow take care of the expansion.

Comparisons with a Standard over the range 200° to 450° C.

The bath employed in this range differs slightly in details of construction from the preceding. The working-fluid used is a mixture of sodium and potassium nitrates in equal proportions; this mixture is sufficiently fluid at 200° C. to allow of efficient circulation.

The bath is made of cast iron of the form shown in Fig. 2. The thermometers cannot be immersed directly in the fused salt owing to chemical reaction which takes place between molten nitrates and the glass. Hence, thin-walled steel tubes are used which are carried from the lid of the bath.

It will be observed that the circulation of hot gases is so arranged that the heating and consequent fusion of the salts take place at the top initially and extends downwards. This is done because heating a salt bath from the lower end generally results in a fracture of the casting on account of the expansion of the salt on heating.

Salt Bath Fitted with Induction Heating System.

A bath using the same working-fluid as that employed in the bath described above, but having a different method of heating, has been designed by Messrs. Fawsett & Parry of the Newcastle-upon-Tyne

Electric Supply Co., Ltd. One limb of a transformer is linked through the bath as shown in Fig. 3. In

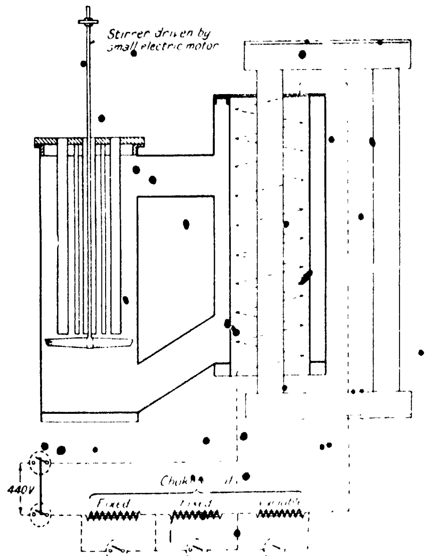


Fig. 3.
Molten-salt Bath Heated by Electromagnetic Induction.

the apparatus illustrated, a potential difference of 440 v. is applied to the coil, the latter being well insulated electrically from the bath, which is of welded steel.

The amount of energy consumed varies from 1 to 3 kW., the temperature obtainable being from 200° C. to about 600° C. The designers do not

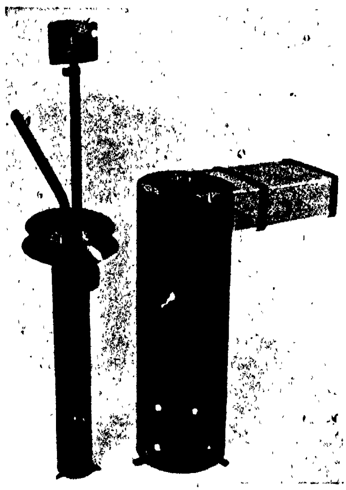


FIG. 4.
COMPONENTS OF MOLTEN-METAL BATH FOR TEMPERATURES FROM 165° C. to 540° C.

consider that the arrangement is ideal, but it serves its purpose and is reasonably efficient.

Molten-metal Bath.

A useful high-temperature bath has been developed by Messrs. Negretti & Zambra. In this bath

a molten alloy is employed as fluid, which permits of the direct immersion of the thermometers in it.

A view of the component parts of one of these baths is shown in Fig. 4, whilst the complete unit is

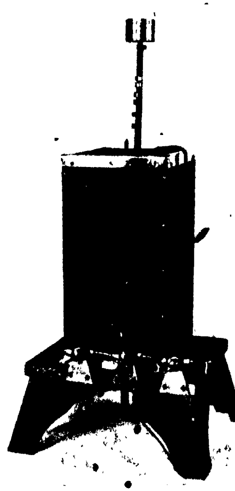


FIG. 5.
EXTERNAL VIEW OF MOLTEN-METAL BATH COMPLETE WITH CASE.

illustrated in Fig. 5. The pots are of steel, oxy-acetylene welded. The inner pot containing the molten metal is cylindrical, and at the top of it there is a centrifugal pump, so that the molten metal can be drawn up from the bottom of the pot through

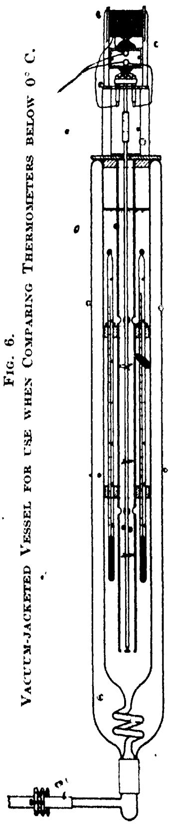


Fig. 6.
Vacuum-Jacketed Vessel for use when Comparing Thermometers below 0° C.

a semi-circular shaped tube running down the whole length of the pot. The centrifugal fan is 1$\frac{5}{8}$ in. diameter, with eight curved vanes welded on, and the fan overhangs the bearings to some extent, so that the bearings are not operating in the molten metal. The diameter of the pot is 2 in. and the length 12 in. Surrounding this pot is a space of $\frac{1}{2}$ in. for taking the hot gases from the burner. These hot gases surround the pot and have their exit near the pump. The whole apparatus is heavily lagged on the outside, and enclosed in a mahogany box.

The gas burner calls for some comment, as it is of a concentric form, with a pilot jet in the centre. Two needle valves control the gas supply, one leading to the pilot flame and the other to the main burner. In operation, it is possible to adjust the pilot flame so that the temperature is maintained constant, and the main jet is used for heating the bath rapidly. A needle valve also controls the supply

of water through a heavy gauge steel tube, which runs down the bath and out again to waste. This is used for cooling purposes.

With regard to the metal used in the bath, this is an alloy of bismuth, antimony, and lead, with a melting point of 165° C., and it may be heated to a temperature of 540° C. This alloy expands in setting; if it expanded on melting there would be a possibility of bursting the pot. In the design of this apparatus, it is very important that the surface metal shall not be broken up unduly when the pump is in operation, otherwise the metal will oxidize and cake up very badly.

Comparisons with a Standard Below 0° C.

Intercomparisons at temperatures down to about −80° C. can conveniently be carried out in the apparatus* shown in Fig. 6.

The vacuum-walled enclosure contains acetone or ether, which is cooled down by the introduction of carbonic acid snow. The liquid must be kept free from moisture, otherwise at low temperatures the moisture separates out as ice crystals and renders observations difficult. The liquid is stirred continuously during the intercomparisons by air bubbling through it, or by means of a propeller enclosed in the central tube as shown.

Temperatures below −38° C. are measured by pentane-in-glass thermometers, and with such thermometers care has to be taken to lower the temperature very gradually, otherwise the viscous pentane adhering to the walls of the capillary may introduce quite serious errors in the observations.

* *Trans. Faraday Society*, Vol. XVIII, 2, 1922

The fixed points enumerated in Table I are available in this region—

TABLE I

FIXED POINTS AVAILABLE FOR THERMOMETER CALIBRATION BELOW 0° C.

Freezing Point of	Temperature on Scale of Helium Barometer.
Carbon tetrachloride	− 22·9°
Chlorobenzene	− 45·2°
Chloroform	− 63·5°
Ethyl acetate	− 83·6°
Carbon disulphide	− 111·6°
Ether (stable form)	− 116·3°
" (unstable form)	− 123·3°
Methylcyclohexane	− 126·3°

It is stated that samples of the above materials, for use in thermometer standardization, can be purchased from the Belgian Office of Physico-Chemical Standards, Brussels.

Mercury Thermometer Adapted for Measuring Surface Temperatures.

To measure with any degree of accuracy the surface temperature of an object is by no means a simple matter. The usual practice in laboratory investigations is to use a thermoelement riveted to the surface. Sometimes, however, it is impracticable to set up a thermoelectric installation and approximate values are sufficient. Messrs. Negretti & Zambra have so arranged the mercury-in-glass thermometer that it can be used for the measurement of surface temperatures.

Referring to Fig. 7, the bulb is enclosed in a closely fitting copper sheath, produced by electric deposition, and to this sheath is attached a flat

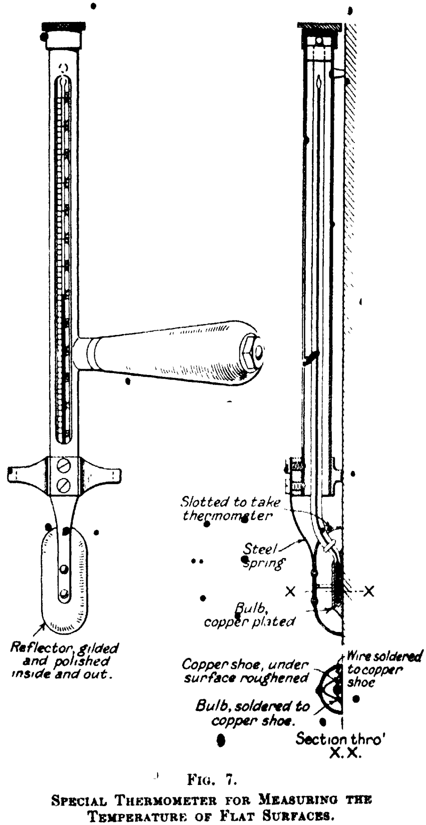


FIG. 7.

SPECIAL THERMOMETER FOR MEASURING THE TEMPERATURE OF FLAT SURFACES.

copper plate to ensure good contact with the surface, while a shield of thin copper serves to minimize the loss of heat from the bulb. The shield is attached to the thermometer by means of a spring in such a way that, when the thermometer is in contact with a plane surface, the periphery of the shield also rests on the surface and screens the bulb, thus reducing both the radiation and convection losses.

By the courtesy of Messrs. Negretti & Zambra, the author is able to quote the results of a series of tests of one of these instruments, made at the National Physical Laboratory. The tests were made on three surfaces—copper, iron, and uralite respectively—each uniformly heated, and the temperature measured by means of thermocouples let into the surface in close proximity to the bulb.

In the first series of experiments the thermometer was left in contact with the surface, and a comparison was made between its readings and those of the thermocouples for a number of steady temperatures up to 300° C. In the case of the iron and copper surfaces, the temperatures recorded by the thermometer were found to be correct to the nearest 5° C. In the case of the uralite surface a similar agreement was found between the thermometers and a thermocouple let in flush with the surface and immediately under the thermometer bulb. The readings of the thermometer were, however, considerably higher than those given by the three thermocouples let into the surface close to, but outside, the area covered by the shield. Thus when these thermocouples read 135° C. the thermometer recorded 155° C. The probable explanation of this difference seems to lie in the fact that the shield of the thermometer reduces the heat loss from

the part of the area which it covers, with the result that owing to the thermal conductivity of uralite being low, an appreciable rise of temperature occurs at this spot. This view is confirmed by the observations, described below, on the effect of bringing the thermometer into contact with a uralite surface which had attained an equilibrium of temperature, and it suggests that the thermometer is not well adapted for giving the true surface temperature of a material of low conductivity.

Lag of Thermometer and Effect of Shield. A further series of experiments was made with a view to testing the lag of the thermometer when brought into contact with a surface which had been maintained for some time at a constant temperature in the neighbourhood of 150° C. The contact of the thermometer produced at first a local fall of temperature, the minimum being reached within a minute. In the case of each metal surface the fall of temperature in the region of contact was less than 5° C. The surface quickly regained its former temperature, and the thermometer registered its final value within three or four minutes from first contact.

In the case of the uralite surface the thermocouple under the bulb fell in temperature 25° C. and then rose to 20° C. above its initial reading. The thermometer appeared to register its final value within ten minutes from first contact.

As suggested above, this local rise in temperature is probably to be accounted for by the reduction of heat loss due to the thermometer shield, coupled with the low conductivity of the uralite. The effect due to the shield was confirmed by removing it, while the thermometer was in contact with the uralite surface. The result was found to be that

the temperature of the surface under the bulb fell 20° C., while the temperature recorded by the thermometer fell 30° C. The error of the thermometer was thus increased by 10° C. The effect of removing the shield was also tried in the case of the copper surface and was found to produce a fall of only 5° C. in the reading of the thermometer, while the temperature of the surface remained steady at 150° C. It should be mentioned that in the experiments above described the surfaces of contact were kept clean. The presence of oxide inevitably increases the lag of the instrument.

Effect of Air Currents. A current of air moving at a rate of 1 ft. per second was allowed to impinge on the copper plate and thermometer when at a steady temperature of 150° C. The draught caused the temperature of the plate to fall, and when the equilibrium state was reached it was found that the thermometer was reading low by 5° C.

Conclusions. (1) The thermometer appears to afford a satisfactory means for measuring the temperatures of plane metal surfaces. It is less satisfactory for surfaces of low conductivity.

(2) The lag of the thermometer when brought into contact with a metal plate at a temperature of 150° C., both surfaces of contact being free from oxide, was found to be of the order of three or four minutes.

(3) The effect of draughts on the reading of the instrument is comparatively small.

Thermometer for Taking the Temperature of the Surface of Hot Rollers.

A modification of the instrument described in the preceding section, adapting it for the measurement

of the temperature of the surface of hot rollers, is shown in Fig. 8, which is self-explanatory.

The three rollers on the frame are adjusted so that the thermometer bulb just avoids contact with

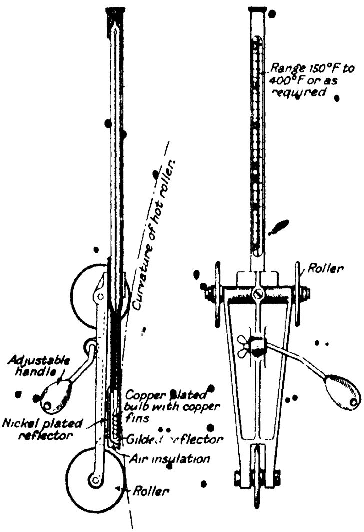


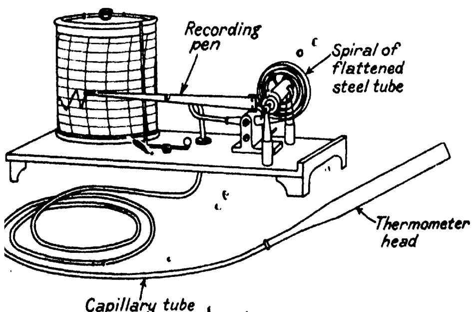
FIG. 8.
SPECIAL THERMOMETER FOR MEASURING THE SURFACE TEMPERATURE OF DRUMS OR ROLLERS.

the hot roller; this prevents the thermometer being heated by friction. The gilded reflector reflects on to the bulb the heat given off by the hot roller, whilst the externally polished nickel-plated reflector

prevents heat radiated from outside bodies from reaching the thermometer. An insulating air space is provided between the two reflectors.

Transmitting and Recording Thermometers.

Next to the mercury-in-glass thermometer the most important instrument of this class is the mercury-in-steel thermometer.



(*Crown copyright.*)

FIG. 9.
TRANSMITTING AND RECORDING MERCURY-IN-STEEL THERMOMETER.

The indicator in some of these thermometers is a Bourdon pressure gauge calibrated to read temperatures directly.

To reduce errors due to varying temperature of the capillary tubing connecting the bulb and indicator in low range thermometers, this is made of fine bore tubing, so that its total capacity is small compared with that of the bulb. In one instrument the temperature of the capillary is compensated for by introducing into the capillary

bore a number of lengths of "invar"; the ratio of the diameter of the "invar" wire to the internal diameter of the capillary being so adjusted that the change in volume of the annular space is just equal to the change in volume of the mercury filling it. The correct dimensions can be determined by calculations, assuming a knowledge of the coefficients of expansion of the steel of which the capillary is made and of the "invar."

It is equally important to correct for changes of temperature of the indicator itself, as there is an appreciable volume of mercury in the flattened steel tube, wound into a spiral which operates the pointer. This compensation is effected by connecting the pointer to the free end of the coiled tube by means of a suitably shaped piece of bimetallic strip.

The general construction of a transmitting and recording thermometer of the mercury-in-steel type is shown by Fig. 9.

Tests on Transmitting Thermometers.

In addition to a calibration in a stirred liquid bath, as described when dealing with the mercury-in-glass thermometer, a distant-reading instrument of the mercury-in-steel type should be subjected to the following tests—

(1) The effect of temperature changes in the indicator.

(2) The effect of temperature changes in the capillary on the indications, the bulb being maintained at a constant temperature.

(3) The effect of pressure changes caused by altering the vertical distance between the indicator and the bulb.

Usually, the indicator is situated in a position

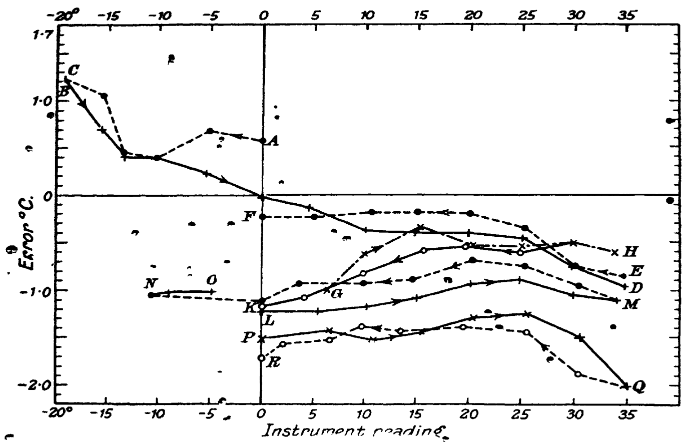


FIG. 10.

TYPICAL CALIBRATION CURVES OF A TRANSMITTING, CAPILLARY-TYPE THERMOMETER.

where the temperature fluctuations are comparatively small, so it is the corrections due to (2) and (3) which need detailed study, although the absence of appreciable error, due to (1), needs verification.

A typical series of observations is shown diagrammatically in Fig. 10. The instrument used for these observations had a capillary about 50 ft. in length.

In the first place, a calibration was made with the dial situated at a height of about 18 in. above the bulb, which was fully immersed, together with about 6 in. of the capillary. Starting from the reading in melting ice the calibration followed the line *AB, CD, EF*.

Secondly, the full length of the capillary was immersed in the bath with the bulb and exposed to the same temperature changes. The calibration now followed the lines *GHK*.

Thirdly, the capillary was partly extended, and the instrument arranged with the indicator at a height of 12 ft. above the bulb. The calibration line *LMNO* was obtained.

Fourthly, the capillary was fully extended, and the instrument arranged with the indicator situated at a height of 50 ft. above the bulb. The calibration line *PQR* was then obtained.

Vapour Pressure Thermometer.

This type of thermometer is of practical interest, for it has been used very extensively for measuring the temperature of the water in the radiators of aeroplane engines. It is also now being used to a considerable extent on motor-cars for a similar purpose.

It is of interest to note that Lord Kelvin designed a thermometer operating on the vapour pressure of

mercury for the measurement of temperatures from 100° to 500° C., and described it in his article on "Heat" in the *Encyclopaedia Britannica*, but the instrument was not taken up at the time.

A diagrammatic sketch of Kelvin's vapour-pressure thermometer is given in Fig. 11. The bulb of the thermometer is freed from air so as to contain only the liquid and vapour of mercury. The pressure is measured by the water manometer. The water column is also freed from air

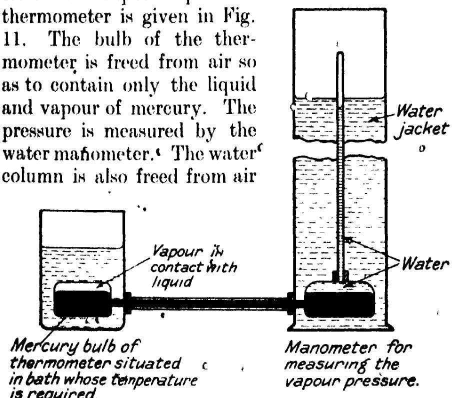


FIG. 11.
DIAGRAMMATIC REPRESENTATION OF KELVIN'S VAPOUR-PRESSURE THERMOMETER.

and the tube sealed. This column is water-jacketed to maintain it at a steady temperature. Below 100° C. the vapour pressure of mercury is too small to be of service in this connection, but there are other liquids such as ether, water, and sulphur dioxide, which can be used.

A typical radiator thermometer is shown in Fig. 12. In this case ether is used, but a number of these

thermometers have been made with sulphur dioxide as working medium.

It will be observed that the readings are independent of the size or material of the bulb, and of the length of the capillary. The instruments do not

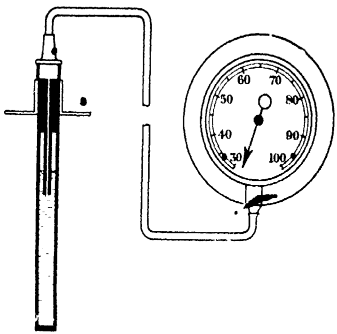


FIG. 12.
RADIATOR THERMOMETER
(VAPOUR-PRESSURE TYPE).

require individual calibration, and the dial indicators can be pointed in the manner adopted for pressure gauges. The scale, of course, is not an even one, as the vapour pressure increases rapidly with the temperature.

In installation, care has to be taken to avoid running the capillary too close to exhaust pipes. The difficulty generally encountered with these thermometers is due to the presence of impurities in the ether, such as water.

CHAPTER III

THERMOELECTRIC PYROMETERS

INTRODUCTION: Edser's *Heat*, pp. 405–408; Watson's *Practical Physics*, p. 504.

IT is a curious fact that when we enter the region above 500° C. it is necessary to employ some form or other of electrical pyrometer, in which the essential element in the equipment is a sensitive moving coil instrument for measuring small voltages. It may safely be asserted that the advent of the millivoltmeter completely revolutionized the technique of high temperature measurements.

Prior to the development of the sensitive moving coil instrument, with its immunity from stray fields and other ailments, pyrometry had chiefly developed along the lines of the expansion pyrometer. The pivoted galvanometer made possible the thermoelectric pyrometer, the resistance thermometer, and the various radiation pyrometers so extensively used at the present day. These pyrometers, although fundamentally different in principle, all involve the use of practically the same grade of moving coil indicator.

Principle of the Thermoelectric Pyrometer.*

If the junction of a pair of two dissimilar metals be heated, a difference of potential is set up and

* These notes, from pp. 28 to 35, pp. 40 to 49, and parts of pp. 81 to 102 inclusive, are reproduced by permission from the author's article on "Electrical Instruments for Industrial Measurements," first published in the *Beama Journal*, Vol. X, p. 18, *et seq.* The information, as now presented, has been revised and modified where necessary.

when the circuit is closed through a current indicator a deflection will be observed. The magnitude of this deflection depends upon the nature of the metals, the resistance of the circuit, and the sensitivity of the indicator (Fig. 13).

After a search in which a variety of different alloys have been tried, pyrometer manufacturers have settled down to the use of one or other of the following combinations —

(1) *Platinum Against an Alloy of Platinum with 10 per cent Rhodium.* This combination is applicable over a wide range of temperature, the upper limit being about 1,500° C. The E.M.F. developed depends upon the individual couple, but the values in Table II are representative

TABLE II

E.M.F. DEVELOPED BY PLATINUM PLATINUM RHODIUM THERMOCOUPLE

Temperature of Hot Junction. (Cold Junction at 0° C.)	E.M.F. in Millivolts.
200	1·45
400	3·37
600	5·54
800	7·92
1,000	10·47
1,200	13·15
1,400	15·95

For research work and most technical measurements, where reliability is the first consideration, this combination of metals is unrivalled. Its disadvantages are the high cost of metals and the necessity for protection from reducing vapours.

(2) "*Chromel-alumel.*" This is the trade name for the alloys—nickel chromium (90 per cent nickel,

10 per cent chromium) and nickel aluminium (98 per cent nickel and about 2 per cent aluminium and silicon and manganese). This combination of two alloys gives a thermocouple which can be employed up to temperatures of 1,100° C. continuously, and

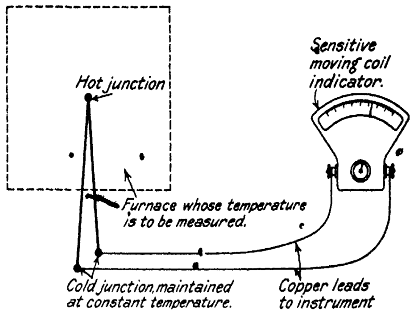


FIG. 13.

DIAGRAM OF ESSENTIAL PARTS OF A THERMOELECTRIC PYROMETER.

The instrument measures the difference of temperature between the hot and cold junctions. In some cases the cold junction is transferred to the instrument terminals B, the use of leads having the same thermoelectric properties as the thermoelement wires.

will stand for short periods up to 1,300° C. For the same temperature difference the E.M.F. generated by this combination is about four times that of the platinum—platinum 10 per cent rhodium thermoelement.

(3) *Copper-constantan.* This couple consists of pure copper and an alloy (60 per cent copper, 40 per cent nickel) known as "constantan" or "eureka." It is used extensively for work at ordinary temperatures, and for experiments on heat transmission

through materials, exploration of the temperature distribution in electrical machinery, etc., it will be found to be of the greatest utility. The metals are easily obtained of the requisite degree of purity and insulated to suit the requirements of the case.

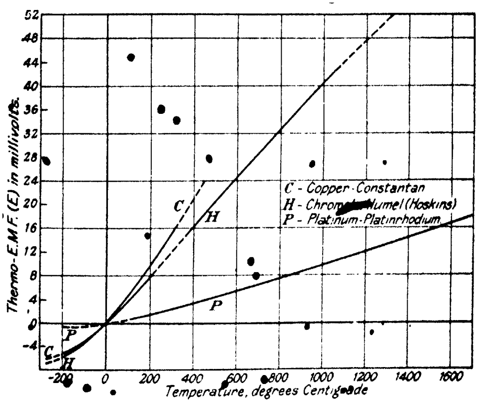


Fig. 11.

VARIATION OF THERMO-ELECTROMOTIVE FORCE WITH TEMPERATURE.

Lines are broken in regions of temperatures in which E.M.F. is not accurately known or in which the couples are not particularly suitable for temperature measurement. (Adams.)

For thermal insulation work the writer has found the following sizes convenient.

No. 26 S.W.G. copper double cotton covered.
No. 26 S.W.G. constantan double cotton covered.
Laid twin, double cotton covered over all, and soaked in paraffin wax.

In Fig. 14 the thermo-electromotive forces obtained at various temperatures are shown for some typical couples investigated by L. H. Adams.*

It is, of course, necessary to study each individual thermoelement if intended for use in accurate measurements, but with a good sample of copper constantan no appreciable variation should be found over a length of several yards of wire.

(4) *Iron-constantan* and *iron-nickel* thermoelements are sometimes used. The defect of iron is the development of parasitic currents when exposed to temperatures of the order of 860° C. These parasitic currents have their origin in a variety of sources. It is believed that segregation and cavities of occluded gas in the casting can give rise to inhomogeneity, whilst changes of crystal structure on prolonged heating is also a frequent source of trouble.

Nickel undergoes a molecular transformation between 230° and 390° C., which renders the metal unsuitable for use in a thermoelement over this range. It gives, however, fairly satisfactory results between 400° and 800° C.

The E.M.F.-temperature relationship of the couple iron-nickel is nearly linear over the working range. A peculiar fact has been observed about nickel; the pure metal is oxidized and rendered brittle by heating in air, whilst its alloys with chromium and aluminium resist oxidation fairly well and do not deteriorate rapidly.

The couple "chromel-alumel" was developed by Hoskins in the course of a search for alloys to replace iron and nickel.

* *Trans. Amer. Inst. Mining Engineers*, 1920.

Protecting Tubes.

Thermoelements composed of platinum and its alloys must be protected from contamination by a closed sheath of glazed porcelain or fused silica. Refractory porcelain tubes will stand up to 1,400° C., but prolonged exposure causes absorption of the softened glaze into the body of the tube. Fused silica tubes can be used up to 1,000° C. in an oxidizing atmosphere free from alkalies. Prolonged exposure to temperatures above 1,000° C. causes devitrification; the material becomes crystallized, loses its mechanical strength, and is then permeable to gases.

Base metal couples do not require the same thorough protection as platinum alloys, so iron, salamander, and fireclay tubes are frequently employed in industrial installations.

Temperature Indicators of the Millivoltmeter Type.

The majority of the thermocouples used in industrial work are equipped with moving coil indicators. The instruments are identical in construction with millivoltmeters, while the scales are generally graduated to read temperatures directly.

The calibration of such an instrument is correct so long as the total resistance of the circuit remains unaltered. When the indicator has a resistance of from 100 to 500 ohms, small variations in the resistance of the leads or of the couple are of no consequence.

An idea of the high sensitivity necessary may be formed when a comparison is made with ordinary voltmeters. With a thermocouple outfit it is often desirable to have a full scale deflection for 10 millivolts, which is only one ten-thousandth of the

voltage which the switchboard instrument has to measure on a 100 volt system.

In order to obtain a robust moving-coil system the indicators fitted to base metal couples sometimes have a resistance as low as 2 ohms, and if the couples are of a heavy section wire, protected from oxidation, the outfits work fairly satisfactory. Special care must be taken with such installations not to cause any alteration of the total resistance of the circuit.

It must be borne in mind that the indications of such an outfit will also be affected by changes of resistance of the leads caused by variations in the temperature of the furnace room. It was observed in the case of an indicator of 5 ohms resistance, that changes of temperature from 0° to 35° C. along 50 ft. of wiring from the thermocouple to the instrument caused the indicator to read 10° C. low at 650° C. So, apart from difficulties due to oxidation and varying depths of immersion of the thermoelement in the hot region, high accuracy cannot be obtained with a low resistance millivoltmeter. With platinum thermocouples the cost of the material prohibits the use of thick wire, and it is therefore necessary to employ high resistance indicators.

In the U.S.A. during the past few years much attention has been given to the development of high resistance millivoltmeters for thermoelectric pyrometry. One maker employs a moving coil wound with aluminium alloy wire of 0·003 in. diameter and, by constructing a very light moving coil, has been able to reduce the size of the control springs so that it has been possible to increase the resistance of the instrument to about 30 ohms per millivolt. The result is an instrument giving full

scale deflection for 40 millivolts with an internal resistance of about 1,200 ohms.

It is doubtful whether this high resistance is really necessary in practice, particularly with base metal couples, but the fact that it is obtainable is worthy of serious consideration and represents a distinct step forward in instrument design.

Potentiometers.

In precision work a potentiometer is employed to measure the E.M.F. in preference to a direct reading indicator.

By the use of a potentiometer the actual E.M.F. is measured, and, since no appreciable current flows through the circuit, variations of electrical resistance of the pyrometer and its leads have no influence on the readings.

The principle of the potentiometer is very simple. Consider a long uniform wire *AB* (Fig. 15) of, say, 1,000 ohms resistance connected to the terminals of a 2-volt cell. Take two points *D* and *E* on the wire. If the terminals of a suitable voltmeter be pressed on the wire at *D* and *E*, the instrument will indicate a certain difference of potential between these two points. The magnitude of this difference of potential is proportional to the product of the resistance between the two points and the current flowing along the wire. By increasing the distance between the points *D* and *E*, any potential difference up to 2 volts may be obtained; whilst, if the points *D* and *E* be very close together, the potential difference will be exceedingly small.

If, now, the leads from a thermoelement be connected to the points *D* and *E*, it will be possible by trial and error to find a position for the points,

such that the electromotive force of the thermo-element is balanced against the potential difference between the points D and E, so that no current will flow in the circuit $DTGE$. The galvanometer G will then show no deflection.

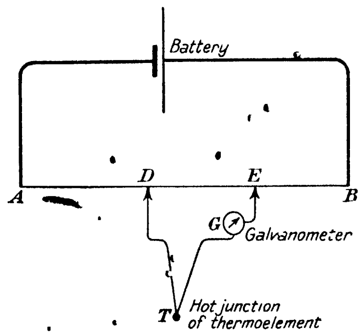


FIG. 15.
ILLUSTRATING THE PRINCIPLE OF THE POTENTIOMETER.

If the current flowing through the wire be known, as well as the resistance per unit length of the wire, it is possible to mark off an E.M.F. scale alongside it, so that any unknown E.M.F. can be measured, provided it is less than 2 volts.

In the form of a long wire, such a potentiometer would not be very convenient for thermoelectric pyrometry, since only a short portion of the wire would be used. To form an idea of the length of such a potentiometer, let us suppose that it is desired to measure the E.M.F.s obtainable with a platinum 10 per cent rhodium couple. It would

be convenient to have the wire so proportioned that 1 mm. on it represents 10 microvolts* (i.e. approximately 1° C. for this combination, see Fig. 14).

Since the E.M.F. of the battery is assumed to be 2 volts, the total length of the wire must be such that the potential difference along its length is 2,000,000 microvolts, and since 1 millimetre corresponds to 10 microvolts, the total length is 200,000 millimetres or 200 metres.

Now the maximum E.M.F. that is likely to require to be measured is only 20 millivolts, and this would be covered by a range of 2 metres on the wire. Hence the remaining 198 metres might as well be coiled up for compactness.

In accurate laboratory work it is convenient to have a more open scale than 10 microvolts per millimetre, say, 1 microvolt per millimetre. In such a case the total length of wire would work out as 2,000 metres, of which 1,980 metres would be in a coil and 20 metres in use. In practice, of course, 1,980 metres of wire would not be coiled, but the same resistance of much finer wire employed.

Now 20 metres is inconveniently long, but a further reduction in the size of the instrument is possible by using one metre length of wire and coiling the remainder into 19 separate coils in series.

When the arrangement of Fig. 16 is considered, it will be seen that by moving the point *D* over a series of studs, to the ends of which the coils are connected, balance may be obtained to the nearest 1,000 microvolts, then by sliding the point *E* along

* A microvolt is one-millionth of a volt, hence 1,000 microvolts = 1 millivolt.

the slide wire exact balance is obtainable, since the range of the wire is 0 to 1,000 microvolts.

Now it is obviously necessary to ensure that the potential drop across the potentiometer is always the same, for an ordinary accumulator cell cannot be depended upon to give exactly 2 volts. In fact, it varies from 1·8 to 2·3 volts. This adjustment is effected

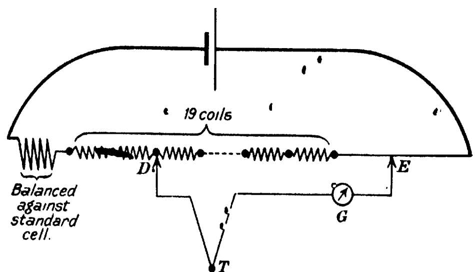


FIG. 16.
ILLUSTRATING THE USE OF COILS TO REDUCE THE LENGTH OF SLIDE WIRE IN A POTENTIOMETER.

by means of a standard cell. A Weston standard cell has an E.M.F. of exactly 1·0184 volts at room temperature, provided no current is taken from it.

Hence, if a coil be arranged in the potentiometer circuit of such a resistance that it is equivalent to a length of potentiometer wire giving 1·0184 volts at its terminals, the standard cell can be balanced across this coil in precisely the same manner as the thermoelement.

The function of the galvanometer is to indicate that there is balance, and to effect this a variable resistance in series with the battery is adjusted until

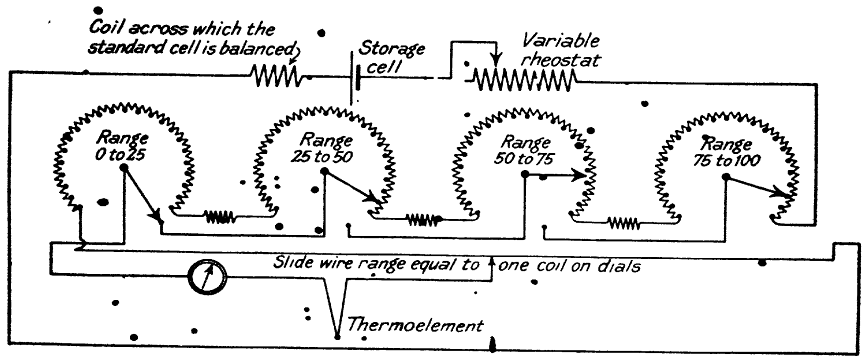


Fig. 17.

Wiring Diagram for Typical Simple Circuit Potentiometer.

(*Methods of Measuring Temperature*, Griffin.)

balance is obtained. This adjustment, of course, is equivalent to setting the current through the potentiometer to a constant value.

A wiring diagram for a typical potentiometer of the simple circuit type is shown in Fig. 17. Here the 100 coils are arranged in four dials of 25 each, and the slide wire is equivalent to one coil.

RECORDING PYROMETERS

In many manufacturing processes where it is essential to keep a continuous record of the temperature of the furnace, it is either necessary to fill up charts at periodic intervals, or arrange that the instrument gives a permanent record. Frequently, when a recording indicator is installed, a direct reading indicator is situated near the furnace to aid the operator, both being connected to the same thermoelement. The fundamental feature necessary is reliability, and this has only been obtained after lengthy experiments, in which many practical difficulties had to be surmounted. The usual form of record desired is that in which temperature appears as one co-ordinate and time as the other. Recorders may be divided into two classes; the one operating on the same principle as a deflection galvanometer, and the other as a potentiometer. The second class of recorders, which belong to the category of "nul" instruments, are considerably more complicated than the first, but, as indicated before, they have the advantage that variations in the resistance of the circuit are of no importance.

Deflection Instruments.

It has not been found practicable to construct a recording millivoltmeter operating a pen in contact

with the paper, as in the case of the ordinary switchboard voltmeter. The forces are so much smaller that the friction between pen and paper would introduce serious errors. Hence a variety of novel devices have been developed whereby the friction between pen and paper is eliminated.

In this connection pyrometry has given a great impetus to the design of electrical instruments, and in the course of time appliances now employed solely on temperature control installations will find application in other branches of engineering.

Space does not permit of a detailed description of the numerous methods which have been tried for marking the chart in a recording instrument, but the fundamental principles employed may be noted—

(1) *Sparking from Pointer to Plate Beneath Chart.* This method was employed in early recorders but it is not much used nowadays. A high-tension circuit is so arranged that at half-minute intervals an electrical spark passes from the pointer to the chart, puncturing the paper. The record is a series of holes with seared edges, which are easily seen. There is a tendency for the spark to jump at an angle, causing a slight error, which, however, is not serious.

(2) "*Chopper Bar*" *Arrangement.* This is one of the most successful of the methods tried. In its original form an inked ribbon was stretched on a metal table beneath the paper. At periodic intervals the chopper bar fell, pressing a point on the end of the galvanometer boom into contact with the paper and against the ribbon and plate beneath. This produced a small dot on the underside of the thin paper which showed through.

In the course of time this device was developed to the form shown in Fig. 18, and in this form it is known as the "thread recorder." An inked thread is stretched between the pointer and the paper. At

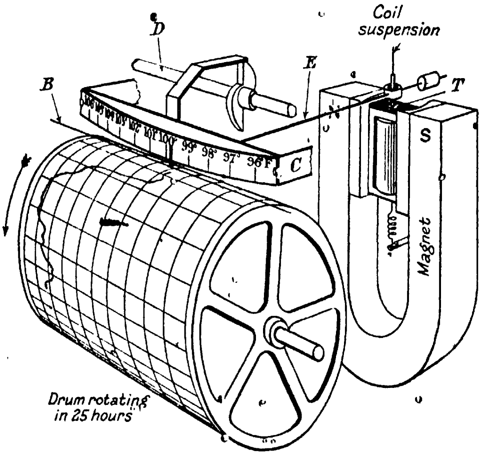


FIG. 18.
ESSENTIAL PARTS OF A THREAD RECORDER.
The drum carrying the record sheet revolves once in 25 hours.

periodic intervals the thread is struck against the paper by the depression of the galvanometer pointer. The thread is slowly carried around inked rollers, so as to expose fresh portions to the pointer and to replenish the ink. By a slight modification a two-colour typewriter ribbon may be substituted for the thread.

The author is not acquainted with the origin of the "chopper bar" idea, but the device was in use on recording barometers thirty to forty years ago. In this case the record was made by a pencil, and the chopper bar kept it in contact with the paper for an appreciable time interval, sufficient, in fact, for the movement to pull it slightly across the paper if a change occurred in this interval.

In addition to the above methods of marking the chart, it might be noted that in aeronautical instruments the use of a radium tipped pointer and a photographic film has been tried with success for giving continuous records. Lumière* has suggested the possibility of using minute jets of gas acting on chemically sensitive paper, for example, H_2S on paper soaked in acetate of lead, and NH_3 on paper soaked in acetate of mercury. Such a method would, however, lead to complications in pyrometry, as it would be necessary to protect the instrument parts from the gases employed.

Recording Potentiometer.

In laboratory work direct reading temperature indicators are rarely employed as greater accuracy is obtainable by the use of a potentiometer. In this the thermo-electromotive force of the couple to be measured is balanced, as already explained, against a definite fraction of the electromotive force of a standard cadmium cell. When this procedure is adopted there is no need to trouble about the actual value of the resistance of the couple and of the leads, or of the constancy of the indicator. Moreover, a higher degree of accuracy in the measurements is rendered possible by the use of

* *Comptes Rendus*, 30th December, 1918.

a sensitive galvanometer working as a "null" instrument.

With the development of the technique of high temperature pyrometry, manufacturers have turned their attention to the possibility of constructing a recording potentiometer which would bear the same relation to the recording indicator as the laboratory potentiometer bears to the deflection instrument.

Recently a recording potentiometer has come into extensive use in the U.S.A. In this instrument a number of thermocouples can be recorded on the same chart, a print wheel being used in place of a pen, and each couple in turn being switched in by an automatic commutator. The essential part of the recorder is the mechanical device for automatically moving the slide-wire contact and the moving pen across the chart (see Fig. 19). The mechanism of this device may be briefly described as follows—

The essential point is that the deflection of a galvanometer results in a movement of the slide-wire contact maker and pen without requiring the galvanometer to do any work. The disc *A* is mounted on a shaft and operates the slide-wire contact by a cord wound on its circumference visible in Fig. 19. The power supplied by a small continuously running electric motor enters the mechanical system through the shaft *B*, carrying the large cams *C* and the small cams *D* and *E*. At each revolution of the shaft *B*, the cams *C* straighten out the arm *F*, which perchance has been tilted a moment before, and in doing this rotate the disc *A*, arm *F* being pressed at this time against the disc *A* by the spring *G*. The arm *F* is pivoted on the spring *G*, which is fast to the frame of the instrument. When the

cams G have rotated until their longest radii are passing the extensions of the arm F, the cam E begins to raise G, lifting F away from the disc. When F is free the cam D raises the rocker-arm H, which, in case the galvanometer is unbalanced,

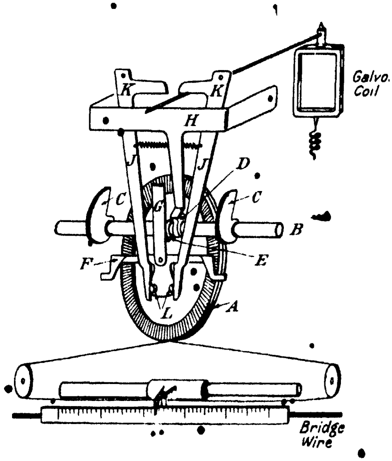


FIG. 19.
MECHANISM OF THE RECORDING POTENTIOMETER.

catches the pointer under one of the right angle levers J pivoted at K. One lever is thus made to swing the arm F by pressing against one of the eccentrically located lugs L. The rocker-arm H is then immediately lowered to allow the galvanometer to swing freely. Cam E is so shaped and fixed on the shaft B that it will recede from the spring G,

allowing G to press F against the disc just before the cams C begin once more to straighten F.

This mechanism, in its cycle of operations, moves the contact on the slide wire whenever the potentiometer is out of balance with the thermocouple, and in so doing operates to obtain or restore the balance. The shaft B rotates once in about 2 seconds, which is slow enough to allow the galvanometer time to come to rest or nearly so. This design is such that the amount of rotation of the arm F increases with the extent of the galvanometer deflection, since the pointer approaches the fulcrum of the levers J as the deflection increases. The motion of H is adjusted so that the rotation of F will correspond to a rebalancing step of the pen of $\frac{3}{4}$ in. (19 mm.) when the deflection is a maximum, and decreases uniformly to about $\frac{1}{50}$ in. when the deflection is just sufficient to catch the boom under one of the right-angle levers. This gives sufficient rapidity of the various actions to take the pen the width of the scale in somewhat less than 1 minute.

A record is made once a minute on the multiple-point recorders of standard design. The position of the pen, when a balance has been obtained just before each record, corresponds to a definite point on the slide wire, for the pen is fixed to the slide-wire contact.

Once during a revolution of the commutator the thermocouple is disconnected and the standard cell connection made. At the same time the potentiometer slide wire is let loose from its shaft and the clutch engages a second resistance. Movements of the disc then result in changing the resistance of the battery circuit and the current is thus set to its proper value. The pen does not follow this adjustment and no record is made of variations in

the current. With batteries in fair condition the current is easily maintained constant; but if there arises any doubt of this constancy, the recorder may be watched for a few minutes and, when connection is made to the standard cell, the first deflection of the galvanometer is an indication of the change in the current since the last adjustment. A short-circuiting contact on the slide wire carries the pen to zero on the chart when the battery has run down, thus providing ample warning under most circumstances.

The scale of this recorder is uniform when graduated in millivolts, and departs from uniformity for a temperature graduation according to the temperature electromotive force relation to the thermocouple. The standard galvanometer is sufficiently sensitive to work satisfactorily with a full-scale range of 10 millivolts, which gives a very open scale, particularly for base-metal couples, when $\frac{1}{10}$ in. (2·5 mm.) of scale corresponds to $2\frac{1}{2}^{\circ}$ C.

Automatic Temperature Control.

Proceeding a step still farther it has been endeavoured to make the control of the furnace temperature fully automatic. An apparatus for automatically controlling the operation of an electric furnace employed for hardening steels has been developed in the United States of America; by means of this equipment it is possible to perform the following operations automatically :

Heat up the furnace interior to a temperature of, say, 1,000° C., or about 100° above that desired in the steel. Hold this temperature steady until the steel being treated reaches the desired temperature (900° C.), when the furnace temperature is

dropped to this value and held there. This cycle of operations is accomplished by placing one thermocouple, called the contact couple, in contact with the piece of steel, and another, called the air couple, in the furnace near the wall. The air couple is kept hot until the contact couple reaches the proper temperature, when the air temperature is lowered to this value.

Various other methods of control have been tried from time to time, particularly with a view to maintaining a furnace at a steady temperature.

It is questionable whether the complications involved in a fully automatic control justifies itself in industrial installations. Supervision of some kind is always necessary, and an attendant provided with a recording pyrometer is able to base his actions upon a knowledge of the changes in the furnace which have been proceeding for some time, rather than upon the instantaneous effect as in the case of a mechanical device.

If the conditions are unfavourable to the installation of a pyrometer, and it is desired to centralize the temperature control of a group of furnaces, then the most satisfactory procedure is to have an attendant to take measurements in a central office and signal to the fireman in charge of the furnaces. Signalling can be accomplished by the use of coloured electric lamps, three of which should be installed at each furnace.

The common practice is to employ the following code. White light indicates that the furnace is at the correct temperature; green that it is too low; and red that it is too high. The combination of white with red, or white with green, indicates a slight departure on the high or low side respectively.

In some large installations the system has been elaborated to include a pneumatic tube connection between the furnace room and the pyrometer station, so that notes can be transmitted between the two points in preference to telephoning.

It might be added that several pyrometer manufacturers have devised automatic methods of light signalling. In the case of the recording potentiometer, already described, two contacts move with the slide wire on its shaft and the third contact is stationary.

Use of Thermocouples for Temperature Measurement in Rotating Parts.

Mr. B. G. Churcher of the Metropolitan-Vickers Electrical Co. has described in the *Journal of Scientific Instruments*,* the method he employed for measuring the temperature of a conductor mounted in a slot of a rotating armature.

Temperature rises of the order of 10° C. had to be measured when the armature was rotating at speeds of about 1,500 r.p.m.

The object in view was the determination of the energy loss due to eddy currents. This loss arises from the magnetic saturation of the armature teeth, and is a function of the degree of excitation of the machine. The tooth saturation causes a considerable flux density to be set up in the slot. As the armature rotates, the slot flux changes in magnitude and sign, and gives rise to eddy currents in the body of any conductor occupying the slot. This loss may seriously affect the performance of the machine.

In the present method this energy loss is obtained experimentally from the thermal capacity of the conductor, and the initial rate of rise of temperature

* Vol. I, p. 310, 1923-4.

of the conductor, when the eddy loss was suddenly set up in it.

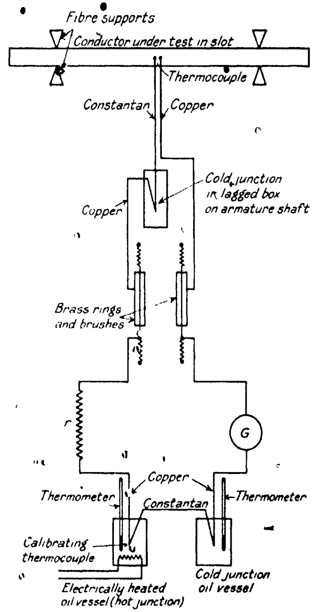


FIG. 20.

CONNECTIONS FOR USING A THERMOCOUPLE TO MEASURE THE TEMPERATURE OF A ROTATING PART.

The conductor was supported in the slot by spacing pieces of very small thermal capacity and heat conductivity, so that the conductor was practically

thermally insulated by air. The top and ends of the slot were closed in order to avoid the effect of draughts. Thermoelements were soldered on to the conductors under test, and connected to a reflecting galvanometer by contact rings mounted on the armature shaft. The connections are shown in Fig. 20.

The procedure in carrying out a test was as follows—

The armature was run at normal speed, with the field magnets unexcited, until the conductor was in temperature equilibrium with the slot walls, and the cold junction temperature constant. This condition was indicated by a steady galvanometer deflection. At a given signal, the exciting current of the machine was switched on. This set up the eddy loss in the conductor.

The rate of temperature rise was then observed with a stop watch, and from these data the initial rate of rise was deduced. This, together with the known thermal capacity of the conductor, gave the eddy loss for that particular speed and degree of excitation.

A number of disturbing factors have to be taken into account in applying this method.

The main difficulty in using thermocouples on a rotating armature is in finding a suitable location for the cold junction. If the difference only of two temperatures is required, such as the difference between the temperatures of a conductor and slot walls, the cold junction is in the slot and only copper leads need be brought to the slip rings. With brass or copper slip rings, there is then little fear of extraneous thermal E.M.F.s unless the rings differ considerably in temperature or small temperature

differences are to be measured. For measuring actual temperatures in commercial tests, where the cold junction temperature is only required to within two or three degrees, it would be sufficient to use an enclosed cold junction mounted on the shaft, and well protected from draughts and heat conduction. Cold junction temperatures could then be measured by thermometer before starting up, and after shutting down. It would, of course, be possible to have a stationary cold junction by using, say, a constantan slip ring, brush and lead connected to the constantan element of the couple, and a copper ring, brush, and lead for the other side.

In the present investigation, an enclosed cold junction mounted on the shaft was used, only copper leads being directly connected to the slip rings. As previously pointed out, it was not necessary to know the cold junction temperature, but only to ensure that it remained constant during a set of observations lasting about one minute. The following tests were carried out to ascertain whether the arrangement was satisfactory—

Slip Rings and Brushes. The rings consisted of brass washers $\frac{3}{8}$ in. thick, mounted on a metal bush keyed to the shaft. The rings were insulated from the bush by a wrapping of micarta and were spaced apart by fibre washers. Six rings were used. Connection to the thermocouples was made by brass rods tapped into the rings and insulated with micarta tubes in the usual manner. In the surface of each ring a V-groove about $\frac{1}{8}$ in. deep was turned. The brush consisted of a single $\frac{1}{16}$ in. brass wire resting in the groove, and making contact over an arc of a few inches length. Contact was maintained by applying tension to the wire by means of adjustable springs at either end. The brushes were continuously lubricated by drops of paraffin. This was supplied by a small tank mounted on the end bracket of the machine, and provided with a tube and small tap for each ring for adjusting the flow of paraffin. With a rate of lubrication of about 30 drops per minute, the wear was very slow. One

brush would last for over a month under these conditions. No trouble was experienced at any time with this arrangement.

Contact Resistance. As the thermocouple readings were taken by galvanometer deflections, it was important that the circuit resistance should remain constant. Tests were therefore made to ascertain whether the slip rings and brushes had appreciable contact resistance. Two rings were short-circuited by a heavy lead, thus forming a circuit consisting of a brush, brush contact, ring, short-circuiting lead, second ring, brush contact, and brush. A low resistance galvanometer was connected in series with this circuit, for use as an ammeter. A known constant E.M.F. was then applied to the circuit, so that the galvanometer was deflected to nearly full scale value. Any change in resistance of the circuit would then alter the galvanometer deflection. The resistance of the brushes, contacts, rings, etc., was obtained by short circuiting this circuit at the brushes with a heavy clamp, as close as possible to the rings, and noting the change in galvanometer deflection. A large number of observations was made with the machine stationary and running at various speeds. The resistance values obtained were erratic but small, and did not appear to bear any definite relation to the speed. The average resistance was about 0·012 ohm, occasionally rising to 0·019, and falling as low as 0·004 ohm. Of this about 0·003 ohm was in the wire brush itself. There is therefore a maximum uncertainty of 0·015 ohm. During the eddy loss experiments the resistance of the galvanometer circuit was never less than 88 ohms. The uncertainty was, therefore, less than 2 parts in 10,000, which is quite negligible.

Thermal E.M.F. To obtain an idea of the resultant thermal E.M.F. at the slip ring connections and brush contacts, two rings were connected together by a heavy wire as in the contact resistance tests, and the two brushes connected to the terminals of a 28-ohm reflecting galvanometer. The machine was then started up and run unexcited at normal speed and the brush lubrication adjusted. The galvanometer deflections were then noted over a period of about three-quarters of an hour. After some initial slow oscillations, the deflection settled down to within plus or minus one millimetre after half an hour's run. It was suspected that part of the observed steady deflection arose from a small homopolar E.M.F., generated by the slip ring connections cutting the unbalanced residual leakage flux of the machine. The direction of rotation of the machine was reversed to eliminate this, and after steady temperature conditions had been reached a difference of only 2·5 microvolts was observed. The final result of the experiment gave a resultant thermal E.M.F. at normal speed and brush lubrication of 3 ± 1 microvolts.

As previously pointed out, a small constant extraneous E.M.F. in the thermocouple circuit does not introduce any error in the

temperature measurements, since an artificial zero is always used. There is, therefore, an uncertainty of ± 1 microvolt. In the eddy loss measurements a temperature rise of about 10 degrees was used, corresponding to a thermal E.M.F. of about 400 microvolts. The uncertainty in the temperature measurements from thermal E.M.F.s at the slip rings is, therefore, not more than plus or minus 0·25 per cent.

E.M.F. of Rotation. In the early stages of the eddy loss measurements, considerable trouble was experienced with both alternating and continuous E.M.F.s of rotation. If the galvanometer sensitivity was adjusted to an adequate value for the temperature measurements, the continuous E.M.F. of rotation was sufficient to send the light spot off the scale with the smallest excitation. On taking an oscillogram of the field form, the cause of this was evident. There were large differences in the maximum induction under the different poles, due to insufficient care having been taken in adjusting the air gaps before the machine was delivered. This caused considerable unbalanced leakage fluxes to be set up, some of which took the form of a radial flux coming out of the shaft. As the slip rings were spaced about a centimetre apart, the connections to the rings formed a conductor of about one centimetre effective length, in which a small continuous E.M.F. could be generated by rotation through the radial flux.

The machine had, therefore, to be dismantled and all adjustments made. After this, the continuous E.M.F. did not cause a deflection of more than about one centimetre. As the deflection due to the thermocouple E.M.F. was about 30 cm., this did not cause any trouble. The elimination of alternating E.M.F.s proved to be entirely a question of carefully twisting the thermocouple leads.

Voltaic E.M.F. It was suggested that there might be some voltaic action between the fibre and the brass rings, owing to the former being soaked with paraffin. On testing, however, no E.M.F. could be traced.

Insulation Resistance. To ensure that the insulation resistance between rings and to earth was adequate, some measurements were made with a 500-volt megger. The lowest resistance found was 14 megohms, the others being several times this value. This is adequately high.

It was noted that immediately the lubrication was shut off large thermal E.M.F.s, and erratic contact resistance, at once appeared.

Calibration of Thermoelectric Pyrometers.

It is advisable to calibrate each individual thermoelement for work of precision, but for industrial use

the calibration of two or three elements of a batch suffices, provided care is taken in the manufacture to produce a homogeneous ingot. If the samples selected for test happen to differ appreciably then, of course, individual calibration is necessary, as the thermoelectric properties are very susceptible to variations in composition due to segregation in the ingot, etc.

Before calibration the wires should be thoroughly annealed. This is readily effected in the case of platinum alloy couples by suspending from the ends and heating electrically to yellow heat. The easiest method of calibrating is by comparison with a standard couple, and this is the method generally employed in standardizing laboratories.

When, for example, a batch of platinum alloy thermocouples have to be tested for E.M.F. at every 100° C. up to 1,350° C., the procedure is as follows—

The outside sheaths and protecting tubes are removed, leaving the wires insulated with fireclay capillaries. The junctions of couples, and that of the standard, are tied together with thick platinum wire, which is wound round to form a little ball. The couples are then inserted in an electric furnace with the junctions in the centre of the furnace.

The electric furnace is constructed by winding thin platinum foil around an unglazed tube of porcelain; connections to the ends being made by a few turns of thick silver wire, tightly wound around the end turns. This tube is contained within a larger tube of fireclay or porcelain, the annular space being tightly packed with calcined magnesia, or alumina, previously heated to high temperatures to ensure full shrinkage. Around the larger tube

3 in. to 6 in. of heat insulating lagging of magnesia asbestos is used.

For temperatures up to 1,100° C. nichrome wire may be substituted for platinum. The furnace is connected to the power mains through an adjustable rheostat by means of which the current is regulated. The couples should not be laid in direct contact with the tube on which the platinum is wound, but inside an inner tube which is carried by two end pieces. The reason for this procedure is that materials, such as porcelain, become electrically conducting at high temperatures, with the result that if the thermocouple wires are in contact with the inside surface of the tube, electrical leakage from the power supply may take place into the thermo-electric circuit. This difficulty is overcome by arranging that there is an air space all round the tube carrying the couples, where it passes through the hot region.

The furnace is heated to a series of steady temperatures and comparisons made with the standard. If the thermocouples are sheathed with porcelain or iron tubes, which cannot be removed, the calibration is much more troublesome. The lag of such pyrometers is considerable and, as metallic contact cannot be obtained between the hot junction of the standard and the couple under test, errors may be introduced on account of irregularities in the temperature distribution in their vicinity.

Under the circumstances the following arrangement may be adopted—

A cylinder of iron or copper is drilled with a number of holes to take the couples, the ends being packed with asbestos. The cylinder is heated in a uniformly heated furnace—which may be a gas

muffle and the comparisons made at a series of steady temperatures. Great care must be taken to obtain steady temperatures since the time lag may not be the same for all.

When there is a large installation of pyrometers, a most important test is the checking of the outfit under working conditions, and this can be effected by a standardized couple and portable potentiometer. Even if the individual pyrometers have been calibrated before installation, it must be remembered that a base metal couple may develop heterogeneity after prolonged exposure to high temperatures on account of structural changes in the alloy. When this occurs, the temperature given by such a pyrometer will depend upon the depth of immersion in the hot region and the temperature gradient along the couple, since the effect of heterogeneity only becomes apparent when the affected portion of the couple is in a region with temperature gradients. Hence it is essential that the conditions of test should correspond closely to those obtaining in actual practice, and this can be achieved by inserting the standard couple in the furnace alongside the other with the hot junctions in close proximity. Observations with the two couples should be taken at a series of temperatures and, if it is impossible to keep steady temperatures, readings should be taken with increasing and decreasing temperatures. When the conditions prevailing in the furnace are fairly definite and the heterogeneity effect small, the observations should give a consistent relationship between the two thermocouples.

It is, of course, useless to expect the same accuracy in a test of this character as would be obtained under laboratory conditions, but the data

should show beyond doubt the reliability of the temperature observations under the working conditions. As check couple, it is advisable to choose one of small cross-section and protected by a thin walled tube.

It is then possible to determine whether the depth of immersion of the working pyrometer is sufficient. When a heavy iron protecting tube is used, as sheath, it may happen that the conduction along the tube is so considerable as to reduce the temperature of the hot junction below that of the region where it is situated.

"Fixed Point Test" on the Check Couple. To verify the permanency of the check couple, it is convenient to check it by the freeze-point of pure sodium chloride at frequent intervals.

For this purpose a small platinum crucible is used about an inch in diameter and an inch high, which is heated in a small electric furnace.

The bare couple is inserted in the molten salt and the freezing point determined in the usual way. Salt of a very high degree of purity can be obtained at moderate cost from various sources, e.g. Messrs. Charles Moore & Co., Ltd., Lymm, Cheshire.

Calibration of Thermocouples by Freeze Points.

The primary calibration of a thermocouple can be effected by observing the melting and freezing points of a series of pure metals and eutectic alloys. A series of such fixed points forms the best set of secondary standards obtainable, provided they are absolutely pure. The basis of the practical scales of temperature accepted by the various national laboratories is a series of freezing points of pure metals, referred to in Chapter I.

Some additional points which might be employed in calibrating thermocouples are given in Table III. The eutectic points are not known to the same degree of accuracy as the pure metals.

TABLE III

FREEZING POINTS SUITABLE FOR USE IN THE CALIBRATION OF THERMOCOUPLES

Substance.	Temperature of Freezing, in C.	Crucible.
Tin	231.8	Graphite or metal covered with charcoal.
Lead	327.4	
Zinc	419.4	
Aluminum-copper eutectic	542	
Aluminum-iron eutectic	649	
Silver-copper eutectic	776	
Silver	961	
Copper	1,083	
Nickel carbon eutectic	1,330	
Nickel	1,452	Refractory clay with borax over metal.

These values for the freezing points of pure metals have been obtained by extremely careful experiments employing thermocouples, which have been directly compared with gas thermometers over the entire range. Hence, by their use, the user obtains a calibration in terms of the gas thermometer.

A suitable general arrangement of crucible and gas-heated muffle is shown in Fig. 21. With the exception of nickel, the metals and alloys should be melted under graphite to preserve them from oxidation. In the case of copper this is of vital

importance, as 0·39 per cent of oxygen (3·5 per cent Cu_2O) forms an eutectic with copper,

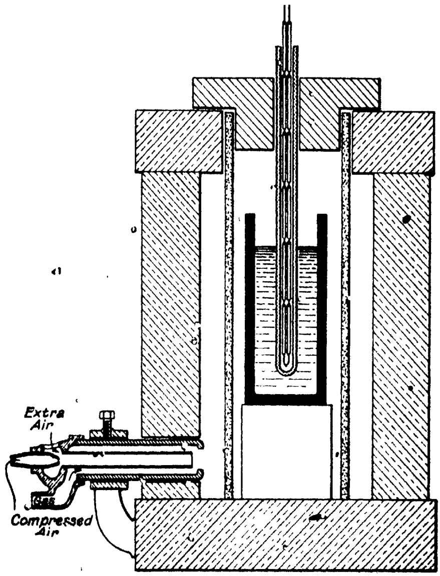


FIG. 21.
CRUCIBLE AND GAS-HEATED MUFFLE FOR METAL FREEZE POINTS.

which has a melting point of 1,065° C. Consequently, if the copper becomes at all oxidized, its melting point may be appreciably lowered. Some workers deliberately oxidize the copper and

use the melting point of the eutectic as a "fixed point."

In the case of the various eutectics, it is as well not to attempt to make up the alloy of eutectic composition, as, just failing to do this, the liquidus would not be distinguishable from the eutectic, but would probably give a spuriously high temperature. By making the alloy so as to contain a few per cent more of one of the metals than the eutectic alloy, the liquidus is easily distinguished from the lower point, which is the one required.

The nickel carbon eutectic point was noticed by Mr. Schofield and the writer whilst endeavouring to find the best conditions for using the freezing point of nickel as a calibration point.

This eutectic gives a very convenient point in the wide gap between copper (1,083° C.) and nickel (1,452° C.).

It is merely necessary to melt the nickel in a plumbago crucible with excess of powdered graphite on the surface.

The nickel point is a difficult one to employ, owing to the high temperature necessary. It can be reached by using a refractory clay crucible with borax glass to protect the metal from oxidation. The borax attacks the crucible with vigour, and, consequently, it cannot survive more than about two freeze-point determinations.

Care must be taken to preserve the purity of the standard metals, so a thermocouple sheath should be set aside for each metal. A bulk of about 100 cc. of metal should be used, and the couple set in the middle of the melt.

If the conditions are correct the melting points and freezing points should agree closely.

The Bureau of Standards (U.S.A.) supplies samples of pure metals for pyrometer calibration.

Aluminium, copper, lead, tin, and zinc are available for this purpose, and it is stated that other metals, such as palladium, platinum, and gold will be added to the series.

CHAPTER IV

RESISTANCE THERMOMETERS

INTRODUCTION: Edser's *Heat*, pp. 399 to 403; Watson's *Text-book of Physics*, p. 685; Watson's *Practical Physics*, Chap. XXIX, p. 507; Watson's *Intermediate Physics*, p. 446.

THE resistance thermometer has several distinct fields of utility. It affords the most convenient means of realizing the absolute scale of temperature over the range from about $-200°$ C. to $+500°$ C.; it is a convenient form of distant reading thermometer for the measurement of air temperatures in cold stores, etc., where a reasonably open scale is desirable; it can be constructed so as to enable very small intervals of temperature to be measured.

As compared with the thermoelement, it has the disadvantages that it is fragile, the bulb occupies considerable volume; it cannot be subjected to the high temperatures which a platinum-platinum-rhodium couple will stand, and it cannot be adapted to measure temperature at a point as can be done with a thermoelement by riveting the junction to the spot.

The Platinum Resistance Thermometer as Working Standard.

The direct approach to the absolute scale is by way of the gas thermometer, but this instrument cannot be used as a working standard owing to its unwieldy character. The general consensus of opinion among scientific workers is that the platinum resistance thermometer is the most convenient means

of realizing the scale of the gas thermometer (and thereby the absolute scale) over a wide range, certainly from − 40° C. to + 500° C., and possibly from − 200° C. up to 1,000° C.

The researches of Callender and Griffiths, which have been amply confirmed by subsequent workers, showed that a parabolic formula represented the variation of resistance with temperature of platinum over the range − 40° C. to + 500° C., hence three calibration points suffice to determine completely the constants of the formula in any particular case.

The points usually taken are the melting point of pure ice, and the boiling points of water and sulphur under normal atmospheric pressures, for the range above − 40° C.

Below − 40° C. the parabolic formula is inapplicable, but a close approximation can be effected over a considerable portion of the range by adding another term and making it a cubic formula.

Calculating the temperatures by the usual parabolic formula for a thermometer standardized in ice, steam, and sulphur, and then directly comparing it with a hydrogen gas thermometer, Henning found that the resistance thermometer temperatures were *too low* by the following amounts—

Temperature by Gas Thermometer.	Amounts by which Platinum Thermometer Reads Too Low.
− 80°	0·1°
− 120°	0·4°
− 160°	1·1°
− 200°	2·3° (extrapolation)

These results apply only to that particular thermometer, for which a was 0·003915 and δ was 1·484.

In the range from 0° down to $-126°$ C. there are a number of fixed points (see p. 4) to serve as calibration points for any type of pyrometer. As, however, there is no other instrument of equal sensitivity available below 0° C., the resistance thermometer affords the easiest method of realizing the scale, employing the table given on p. 4.

There is, of course, a check point available in the boiling point of oxygen, but it must be remembered that there is no justification for using the fixed points—melting ice, steam, and the boiling point of oxygen—for fixing the constants of a parabolic formula for use in the range $-200°$ C. to $+100°$ C.

It is not proposed to deal here with the details of the calibration of resistance thermometers to serve as working standards for reproducing the temperature scale: for this, reference must be made to the larger treatises mentioned in the bibliography.

Instruments for commercial measurements, comprising a resistance thermometer and indicator or recorder, are calibrated by means of the equipment already described in the case of the mercury thermometer, and thereby the corrections for both thermometer and indicator are obtained in a single operation.

A description will now be given of some novel equipments utilizing the resistance thermometer.

Ohmmeter Type of Resistance Thermometer Indicator.*

The principle of the ohmmeter has been utilized in the design of temperature indicators, as by this

* An electric transmitting radiator thermometer, *Proc. Phy. Soc.* Vol. XXXIII, p. 141, 1920.

means the indications of the instruments are rendered independent of variations in the battery current, provided they do not exceed certain limits. The instrument described below was one used on an aeroplane for indicating the temperature in the radiator; two thermometers being connected to the same indicator through a change-over switch.

The resistance thermometer is made of platinum wire, wound on a strip of micanite. The coil is

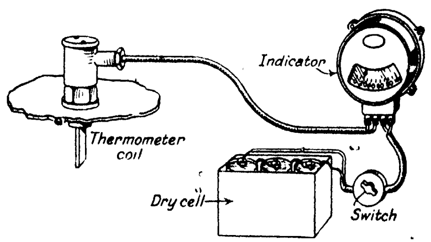


FIG. 22.
GENERAL ARRANGEMENT OF ELECTRICAL RESISTANCE THERMOMETER.

enclosed in a flat copper tube, forming part of a brass elbow which screws into the radiator. The resistance of the thermometer coil at zero centigrade is about 90 ohms; this high resistance is desirable in view of the fact that no compensation is applied for the change in resistance of the connecting leads, and the variation in these leads would be important with a low resistance thermometer. A push-button switch forms part of the equipment, so that the current is only used during the actual observation.

The indicator (Fig. 22) is a miniature form of the well-known simple ohmmeter; it is based on the

moving coil principle. The two coils are wound crosswise on the same aluminium frame, and move freely in a powerful magnetic field. One coil is connected through a resistance across the battery (see Fig. 23), and circuit connections may be traced from the battery by conductors 1 and 10, resistance 11, conductor 12, coil 13, conductor 7, resistance 8, and conductor 9 to the battery. The other coil is connected in series with the resistance thermometer. Circuit connections may be traced from the battery by conductors 1 and 2, resistance 3, conductor 4, through the thermometer, by conductor 5, coil 6, conductor 7, resistance 8, and conductor 9 to the battery.

The indication is thus the ratio $\frac{\text{electromotive force}}{\text{current}}$, i.e. the resistance of the thermometer circuit. The reading is theoretically independent of the pressure employed, but actually the E.M.F. must be kept within limits; otherwise, if the E.M.F. is too low, friction decreases the sensitivity, and if too high, the current causes appreciable heating up of the resistance thermometer above its surroundings.

The same rule should, in fact, be used here as in the case of the laboratory platinum thermometer; the current should always have about the same value as that used in the calibration of the instrument.

It will be evident from the principle of this instrument that, owing to the absence of any control spring, the pointer always remains at a position somewhere away from the zero, depending on the last reading taken. This apparent reading would prove somewhat deceptive, and therefore requires to be eliminated by some form of clamp for setting the pointer back to zero. The clamp in this

particular instrument consists of a small arm, pivoted about a vertical axis, and arranged to hold the pointer at zero by the action of a spring. When the current is switched on, the arm is immediately

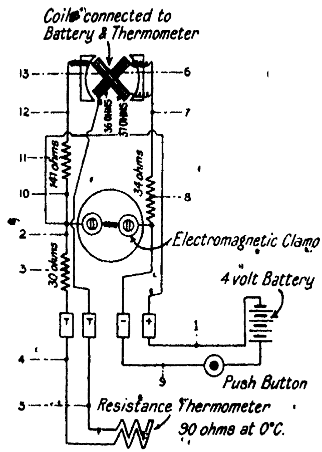


FIG. 23.
CONNECTIONS OF RESISTANCE THERMOMETER.

swung round beyond the top of the scale by a small electromagnet connected across the battery, and remains fixed while the reading is taken. As soon as the current is switched off again the arm is released and returns the pointer to zero.

This device will be clear from Fig. 23. The scale of the instrument is very cramped, owing chiefly

to the large angle subtended by the cross coils (60° in this case). The graduation is, moreover, not uniform, but closed up in the central part of the scale, making the calibration somewhat troublesome. It would, of course, be an improvement to use a smaller range of temperature for the purpose of controlling the temperature of the water in the radiator (instead of 0° to 100° C., as in this instrument).

Recording Thermometer for Clinical Work.

In medical research it is necessary at times to obtain continuous records of the body temperature over an interval of several hours, and with an open temperature scale.

An instrument used for this purpose was described by Mr. R. S. Whipple in a paper published in the *Journal of the Institution of Electrical Engineers*, April, 1920. The resistance thermometer was of the usual pattern platinum wire wound on a mica cross and enclosed in a silver sheath.

The arrangement shown in Fig. 24 consists of a Wheatstone's bridge in which the thermometer forms one arm; balancing coils being arranged in the opposite arm to balance the resistance of the thermometer at any predetermined temperature. The ratio coils are equal.

The galvanometer, which is of the moving-coil type, is connected across the arms of the bridge, and it is the deflections of the coil that are recorded. For the small angle through which the coil is deflected (maximum about 25°) the deflections are proportional to the amount the bridge is out of balance, viz. to the change in resistance of the thermometer coil with a given change in temperature. In a direct deflection method such as this, it is obvious that the

galvanometer deflection must depend on the electromotive force of the battery, and what few complica-

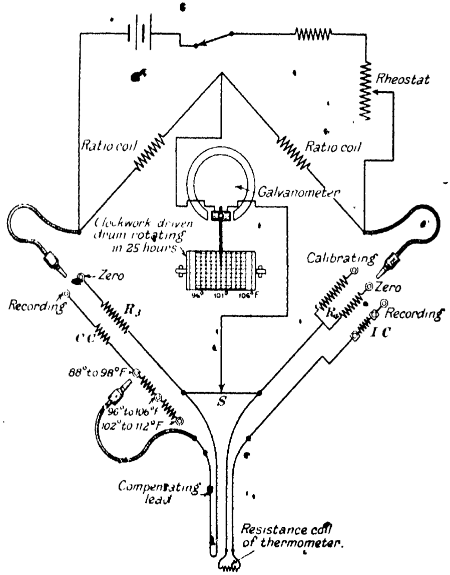


FIG. 24.
CIRCUIT DIAGRAM OF RESISTANCE THERMOMETER FOR CLINICAL WORK.

tions there are in the apparatus have had to be introduced to control this. The method of adjusting the apparatus is simple.

Before the battery circuit is closed, viz. with the

switch in the "off" position, the zero of the galvanometer is determined. This should be on the line corresponding to the lowest temperature (say, 96° F.) recorded by the thermometer. If it is not, the pointer is readily brought into the desired position by rotating the torsion head from which the galvanometer coil is suspended.

The electrical zero of the bridge the one in which no current is passing through the galvanometer coil when the battery switch is closed—is then determined. The plugs attached to the heavy flexible leads, and shown symmetrically on both sides of the diagram, are placed in the zero positions. It will be observed that the thermometer coil and its leads, and the corresponding balancing coils and compensating leads, are then cut out, the ratio coils being balanced against the coils R_3 and R_4. If, when the switch is closed, the galvanometer is not deflected, the electrical zero is correctly adjusted. If it is deflected, the slider S is moved on the slide wire until balance is restored. The instrument must then be adjusted so that the galvanometer coil is deflected through a definite angle for a given change in the resistance of the thermometer. Experience showed that the making of the test by heating or cooling the thermometer was tedious, and as the test should be made every 24 hours, it was advisable to introduce a test resistance which would be equivalent to an increase in the resistance of the thermometer for a given change in temperature. In practice, a manganin coil having a resistance equal to the increase in resistance of the thermometer coil, for a rise in temperature of 10° F., is used. This is marked "calibrating," and is shown in the right of the diagram. When this is introduced the galvanometer

should be deflected and the pointer should read 106° F. If it reads low then the electromotive force on the bridge is not sufficiently high, and should be raised by cutting out some of the battery resistance by means of the rheostat. In the same, say, if the galvanometer reading is too high, the electromotive force should be reduced. In the later form of the instrument the sensibility is altered by an adjustable magnetic shunt, thus avoiding the use of a rheostat.

These various adjustments having been made, the two plugs are placed in the "recording" position and the apparatus is ready for use. The travelling plug (Trav.) is placed in the hole corresponding to the temperature range desired, the usual one being 96° to 106° F. By introducing or cutting out the coils shown in the arm of the bridge opposite to the thermometer, the range over which records can be obtained may be varied. The ranges generally used are 88° to 98° F., 96° to 106° F., and 102° to 112° F.

Air-temperature Outfit for Survey Work.*

The effects of atmospheric refraction are of considerable importance in survey work, so the Indian Survey Department has, in conjunction with the N.P.L., designed an outfit for measuring the distribution of temperature in the atmosphere from the ground up to a height of 150 ft.

A number of resistance thermometers are connected in series with a standard coil of manganin. A constant current is maintained in the circuit, and the volt-drop over each thermometer is measured in turn, by means of light potential leads connected

* Report of the N.P.L., 1921.

to a potentiometer, and is compared with that over the standard resistance.

Referring to Fig. 25, which shows the general

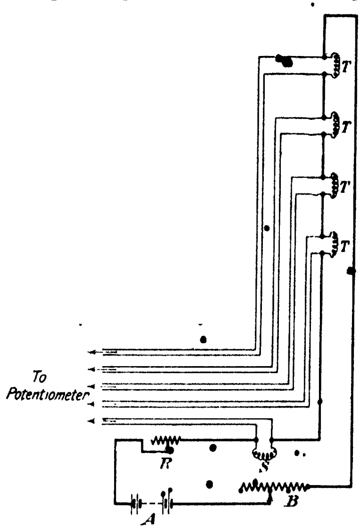


FIG. 25

GENERAL ARRANGEMENT OF RESISTANCE THERMOMETERS USED FOR AIR-TEMPERATURE MEASUREMENTS IN SURVEY WORK (SEE ALSO FIG. 26).

arrangement of the circuits, A is a battery of dry cells capable of maintaining a current of about 0·01 ampere in the circuit; R is an adjustable rheostat; S is a standard manganin coil of 25 ohms; T, T, T, are platinum resistance thermometers, each

having about 26 ohms resistance at 0° C. and a fundamental interval of 10 ohms. Light potential leads run from S and from T, T, T, to a potentiometer through a selector switch. The whole circuit, apart from the platinum thermometers, is of manganin, and a swamping resistance B of 1,000 ohms of manganin is also included. Fluctuations in the

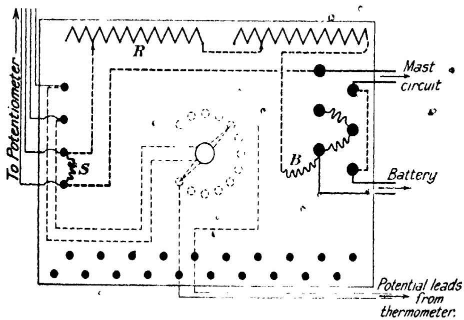


FIG. 26.
CONNECTION DIAGRAM OF BOX CONTAINING STANDARD RESISTANCE, RHEOSTAT, SWAMPING RESISTANCE, AND MEASUREMENTS (SEE ALSO FIG. 25).

current, due to temperature changes in the circuit, are thus rendered negligible.

A diagram of the connections of the box containing the standard resistance, rheostat, swamping resistance, and the selector switch for the potential leads is shown in Fig. 26.

Each platinum thermometer in this outfit consists of a strip of platinum 12 mils wide, 2 mils thick, and about 14 ft. long, wound on a framework of

four mecanite-covered pillars held by cast iron ends. Cast iron was chosen because its coefficient of expansion was not very different from that of platinum, so the possibility of strain by temperature changes was diminished.

The thermometers were protected by perforated sheet metal and supported inside large screens of aluminium-painted balloon fabric. These consisted of three horizontal layers of fabric above the thermometer and two horizontal layers below, their object being to prevent solar and terrestrial radiation from affecting the instrument.

A portable type of potentiometer was employed reading from 230 to 330 millivolts, and the sensitivity was such that the temperatures could be read to about 0·02° C.

Temperature of Generator Field-coils.

On some of the American ships, fitted with electric propulsion, indicators are installed to show the temperature of the field windings at any moment. A diagrammatic view of the instrument is given in Fig. 27. It consists of a potential and a current element. The vanes are attached to a common movable shaft at such an angle with respect to each other, that, when the two stationary coils are excited the torques produced in the vanes are in opposite directions.

There is no spring control on the movable shaft, so that the resultant position taken up by the shaft depends only on the ratio of currents in the two stationary coils; or, since one coil is connected across the field, and the other in series with the field, it depends on the ratio of volts applied to the field coils of the generator to the current in the field, i.e.

the resistance of the field coils. Since the temperature coefficient of the resistance of copper is known, the instrument is calibrated directly in temperature. The instrument must, of course, be calibrated for the field to which it is to be connected.

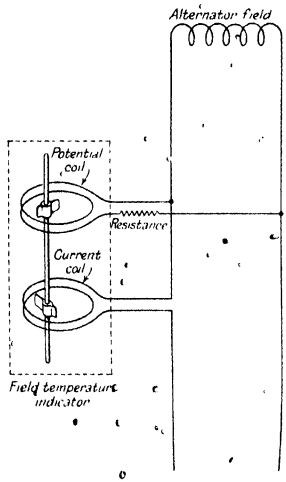


FIG. 27.
TEMPERATURE INDICATOR FOR FIELD COILS OF ALTERNATOR.
The two coils and the spindle lie in the plane of the paper.

Temperature of Underground Cables for Electrical Supply.

Overloading of supply mains has to be carefully guarded against, and the most satisfactory way of

doing this is to observe the temperature of the cable.

In a system developed by Messrs. Siemens Bros., a nickel wire is incorporated in the cable, but well insulated from the conductors. This nickel wire forms one arm of a Wheatstone's bridge, the other three arms being mounted behind the panel carrying the indicator or recorder in the power station.

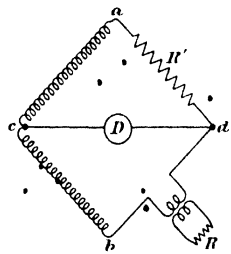


FIG. 28.
DIAGRAMMATIC REPRESENTATION OF A.C. RESISTANCE THERMOMETER AS USED FOR HOT SPOT MEASUREMENTS IN TRANSFORMERS (SEE ALSO FIG. 29).

Thus, by observing the indicator, the engineer can ascertain the temperature of the nickel wire and hence keep watch on the cable.

Temperature Indicator for Transformer Winding.

To operate transformers so as to obtain the maximum output, and yet not endanger the insulation by overheating, is a problem which needs an accurate knowledge of the " hot spot " temperatures

for its solution. Of the various simple schemes which have been proposed for measuring the hot spot temperatures, the resistance thermometer with the resistance unit actually embedded in the windings, and at the same time insulated from the temperature-indicating instrument, has proved to be the most promising.

The novel feature of the device to be described is the method of insulating the thermometer unit (which may be at 27,000 volts or so) from the indicator, and hence the operator.

The arrangement is, essentially, a Wheatstone's bridge supplied with alternating current instead of continuous (see Fig. 28). Two arms of the bridge, *ac*, *cb*, are formed by the secondary winding of a potential transformer; the third arm by a constant resistance R^1; and the fourth arm by the primary winding of a transformer, the secondary of which is connected to a non-inductive copper resistance R, which is imbedded in the winding of the transformer whose temperature is to be measured.

Referring to the wiring diagram shown in Fig. 29, an alternating E.M.F. E is applied to the primary winding of the potential transformer; and a secondary E.M.F. E^1 is induced between the points *a* and *b*. Between these two points are three circuits, two of which, *acb* and *adb*, form the bridge, while the third *ab* is the fixed coil circuit of a separately-excited dynamometer D. As the temperature of the transformer changes, the resistance of the copper unit R changes, thereby affecting the balance of the bridge. The dynamometer, with its movable coil connected across the points *dc*, denotes the amount that the bridge is out of balance. The scale is marked in temperature ranging from

20° to 140° C. The thermometric element consists of two insulated copper wires, wound spirally about a flat insulated copper core, and joined together at one end of the unit, which makes it non-inductive. The unit is from 20 to 25 ft. in length, and is placed either between the turns or the strands of the coil, depending on whether one or more strands per turn is used.

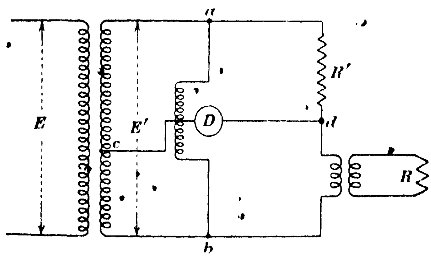


Fig. 29.

Connection Diagram for A.C. Resistance Thermometer (see also Fig. 28).

To prevent the resistance unit forming a floating conductor (electrically speaking) in the transformer, one point of the unit is solidly connected to the adjacent conductor of the main coil. The potential of the unit being the same as that of the adjacent conductor, it is necessary to use only a light insulation.

Since the reading of the meter will change with a change in the exciting voltage, except when the bridge is balanced, it is necessary to correct for this.

The conditions are so arranged that the bridge is balanced at the most important temperature (about

100° C.); as the temperature varies from 100° C. the error due to changes in voltage increases.

To correct for this, the primary side of the potential transformer is provided with several 5-volt taps. By this means the operator is able to adjust the secondary voltage to within about 2·5 per cent of its designed value.

REFERENCES—

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"Development in Switchboard Apparatus," *ibid.* Vol. 20, p. 381; 1917.

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CHAPTER V

OPTICAL PYROMETRY

THE upper limit to the use of a thermoelement is about 1,400° C. and although it is possible to use the platinum-platinum 10 per cent rhodium element up to 1,550° C., it is very costly to do so, for the wires deteriorate rapidly at these high temperatures.

Fortunately there is available a number of different types of radiation pyrometers suitable for work up to the highest temperatures, so there is no justification for forcing the thermoelement beyond its safe working temperature.

Pyrometers based on the laws of heat and light radiation have the great convenience that it is not necessary to submit them to the extreme temperature to be measured, and it is on this account that they are of such utility in industrial work.

It is proposed to deal here only with one of the variety of optical pyrometers available, namely, the disappearing filament type. This instrument is based on the well-known fact that the intensity of the light emitted by a hot object increases as the temperature is raised.

Temperature and Luminous Intensity.

Theoretical and practical researches have shown that the relation between the light of any particular colour or wavelength emitted from an incandescent surface, and the temperature of the latter is a very

simple one if the surface, when cooled down, is dead black in appearance. The theory by which the laws are deduced postulate a perfectly black surface, and this implies a somewhat ideal surface, very different from those of polished metals. Untreated carbon is a very close approach to this ideal.

It has been discovered, as the result of these theoretical researches, that the light projected through a hole in an incandescent enclosure, such as a furnace uniformly heated, is practically identical with that which would be emitted by a perfectly black surface. This was a discovery of fundamental importance, since it permitted the application of the simple theoretical laws to the computation of the temperature of furnaces, muffles, etc. Of course, it is not always permissible to assume that the walls of a furnace are absolutely uniform in temperature, but usually the variations are not of such serious magnitude as to cause big errors in temperature measurements.

According to the law discovered by Wien, the relation between the intensity E of the light of any particular wavelength λ, and the temperature of the perfectly black surface is given by the formula—

$$E = \frac{C_1}{\lambda^5 \varepsilon^{\frac{C_2}{\lambda T}}}$$

where C_1 and C_2 are constants.

This formula is based on plausible assumptions concerning the mechanics of the radiation emission from atoms, and represents with fair accuracy the distribution of energy in the spectrum, but it fails for large values of λ or of T, i.e. if the product λT exceeds 3,000.

Planck's formula—

$$E = \frac{C_1}{\lambda^5(\varepsilon^{\frac{C_2}{\lambda T}} - 1)}$$

is capable of representing the experimental facts over the entire range, but is scarcely more than an empirical formula. Its deduction from theoretical considerations requires assumptions which are irreconcilable with the fundamental principles of electrodynamics.

It will be observed that Planck's equation reduces to that of Wien's for small values of λT. Hence, in practical pyrometry, Wien's form is generally employed on account of its convenience in its logarithmic form—

$$\log E = \log\left(\frac{C_1}{\lambda^5}\right) - \frac{C_2}{\lambda T}$$

i.e. a linear relation between log E and $\frac{1}{T}$.

The isolation of a particular wavelength of light λ, or more accurately a narrow spectral band, from the continuous spectrum of the perfectly black surface is effected by the use of a special red glass which is inserted in the eye-piece of the instrument.

Limitations of Filter-type Optical Pyrometers.

There are a number of pyrometers in use which have no theoretical basis whatsoever. Inventors have frequently attempted to produce optical pyrometers, utilizing the fact that it is possible to cut off the light from the hot object or furnace by interposing in front of the observer's eye a screen of graduated absorption value. The temperature

is then estimated by the thickness of the smoked glass or other absorbent required to just extinguish the light. Unfortunately, however, such instruments assume that the human eye has a constant sensitivity. Now it is a well-established fact that big variations in the sensitivity of the eye are produced by fatigue and other uncontrollable factors. Then again, different observers have not the same acuity of vision as regards the minimum intensity of luminous radiation perceptible to the eye. The experiments of Abney and Watson* indicate that for red light this threshold intensity may vary five-fold for different observers. Such an increase in luminous energy would be caused by a temperature change of the order of 100° C. in the region of 1,000° C., so that occasional errors of this order must be expected with instruments of this type. The alternative is to employ in the design of pyrometers a source of light to serve as a standard for making comparisons. The eye is then used only for matching and no assumption has to be made as to constancy.

A variety of pyrometers have been designed in which either an electric lamp or an amyl acetate flame is the standard of reference. An electric lamp, if properly aged, has many practical advantages over the amyl acetate flame, and it is probable that in the course of time it will entirely supplant the flame in industrial pyrometers.

The Disappearing Filament Type Optical Pyrometer.

This type of pyrometer was introduced about twenty years ago by Morse in the U.S.A., but the principle involved—the matching of the brightness

* *Phil. Trans. Roy. Soc.* Vol. 216, p. 91, 1916.

of a lamp filament against that of the hot object—was in use as far back as 1888. In its earliest form the Morse pyrometer (Fig. 30) consisted of a metal tube about 3 in. in diameter and 8 in. long, open at both ends, and provided on one side with a projection serving as a means for holding an incandescent lamp-holder. At the centre of the tube was mounted the

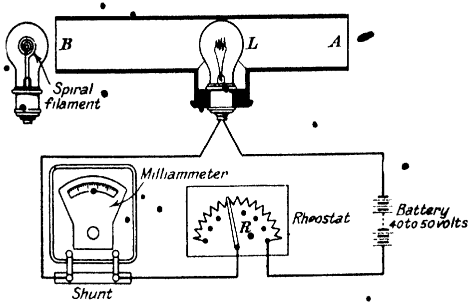

FIG. 30.
DIAGRAMMATIC REPRESENTATION OF MORSE OPTICAL PYROMETER.

lamp, which was connected in series with a battery, rheostat, and milliammeter.

In making a temperature measurement the operator holds the pyrometer in front of his eye, and, looking through, observes the lamp filament superimposed on the furnace or hot object as background. Owing to the different distances of lamp and furnace from the observer it is necessary to vary the accommodation of the eye when looking at one object and then the other. By adjustment of the rheostat the current in the lamp is varied

progressively until the lamp filament and furnace appear equally bright. When the filament disappears against the furnace as background, the current through the filament is a measure of the temperature.

The consistency of results that can be procured with this somewhat crude device is rather surprising. The writer recently found one in works' use where the instrument had been simply constructed from a large cardboard tube and a 100 watt lamp.

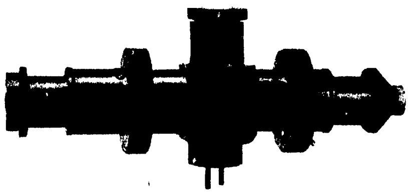

FIG. 31.
MODERN FORM OF THE DISAPPEARING FILAMENT OPTICAL PYROMETER AS MADE BY SIEMENS BROS., LTD.

Soon after the introduction of the Morse instrument, several investigators improved it by adding an objective and an eye-piece. The objective projects an image of the furnace upon the plane of the lamp filament, and the fatigue of the eye due to constantly varying the accommodation is avoided. The modern form of the instrument comprises a telescope, a variable rheostat, battery, and ammeter. The ammeter readings are converted to temperatures by the aid of a table or chart. Fig. 31 illustrates one modern form of this pyrometer as manufactured by Messrs. Siemens Bros.

In order to obtain a compact portable instrument

for use in the furnace room, the writer constructed the instrument shown in Fig. 32. In this the telescope, ammeter, and rheostat are a self-contained unit. The scale of the indicator is graduated to read temperatures. The handle of the rheostat is not shown, as it is on the opposite side to that taken in the photograph. The battery, of course, is

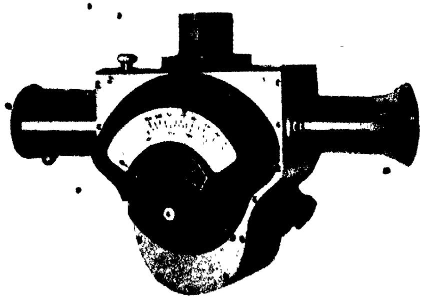

FIG. 32.
PORTABLE SELF-CONTAINED OPTICAL PYROMETER.
Telescope, lamp, variable rheostat and ammeter in one unit.

separate. Two scale ranges are obtainable by the use of a dark glass screen; the ranges on the present instrument being 700° to 1,400° C.; 1,000° to 2,500° C. (with absorption screen interposed). The instrument was calibrated over the range 700° to 1,400° C. by observations on a furnace the temperature of which was measured by a thermo-element. The higher range was obtained by theoretical calculation based on the data obtained in the calibration at the lower temperatures.

Should the lamp be broken it is possible to replace

it without re-engraving the scale, for, from a large batch of lamps, a number can be selected which have practically identical temperature-current values.

It may be of interest to quote a typical set of values for lamps of the type employed in optical pyrometry; these are given in Table IV.

TABLE IV

TYPICAL VALUES OF TEMPERATURE AND FILAMENT CURRENT FOR DISAPPEARING FILAMENT TYPE OPTICAL PYROMETER

Temperature, °C.	Current through filament, in amperes.
700	0·20
800	0·23
900	0·26
1,000	0·29
1,100	0·32
1,200	0·35
1,300	0·39
1,400	0·43

From these data it will be observed that the full scale of the ammeter cannot be utilized since the lamp requires about 0·2 amp. before the filament begins to glow. Consequently ammeters with "set back" zeros are sometimes employed with optical pyrometers.

The ammeter shown on the portable pyrometer (Fig. 32) is not well adapted for much "set back" of zero. A more satisfactory type of ammeter would be one with the pole shoes and core so shaped that the first part of the scale was contracted and then opened out over the working range.

An instrument developed from the design of Fig. 32 is shown in Fig. 33. This instrument is manufactured by the Cambridge Instrument Co.

Another method of overcoming the difficulty of the contracted scale is that devised by Mr. F. H. Schofield.* It consists essentially of a bridge, of which the pyrometer lamp forms one arm (see Fig. 34). The other arms a, a, and d are of manganin. The value of d is so chosen that with the

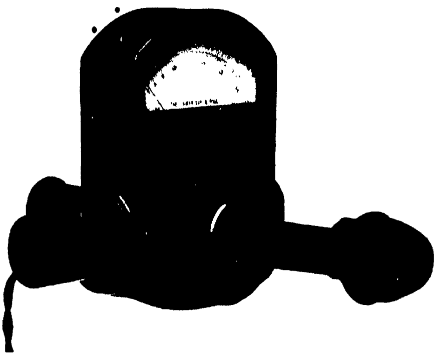

FIG. 33.
PORTABLE SELF-CONTAINED OPTICAL PYROMETER OF THE DISAPPEARING FILAMENT TYPE AS MADE BY THE CAMBRIDGE INSTRUMENT CO.

filament running at any particular temperature (say, 700° C.) the bridge is balanced. The zero of the scale thus corresponds to a reading of 700° C. If, now, the current in the bridge be increased by adjusting the rheostat r, the temperature of the lamp increases and its resistance changes. The other arms remaining unchanged in resistance, this will cause an out-of-balance deflection in the

* *Journal of Scientific Instruments*, Vol. 1, No. 7, April, 1924.

galvanometer. The resistance b in series with the galvanometer, which controls its sensitivity, is fixed at such a value that the extreme end of the scale is made to correspond to a certain upper limit of temperature (say, 1,300° C.). Thus the desired temperature range (700° - 1,300° C.) is made to fill

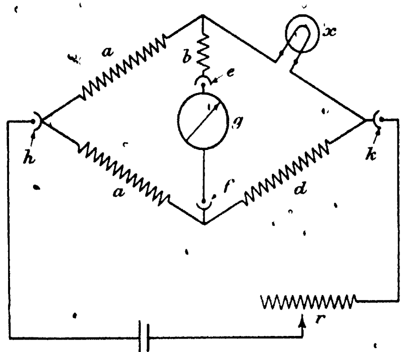

FIG. 34.
CONNECTION DIAGRAM OF OPTICAL PYROMETER USING A BRIDGE CIRCUIT TO SECURE AN OPEN SCALE.

exactly the whole length of the galvanometer scale.

The relation between the current C_g through the galvanometer and the current C through the lamp arm of the bridge can be shown to be—

$$C_g = \frac{a(x - d)}{2ad + g(a + d)} C,$$

g being the total resistance of the galvanometer and

series resistance b, and x that of the lamp arm of the bridge. Thus—

$$C_g \propto (x - d)\,C.$$

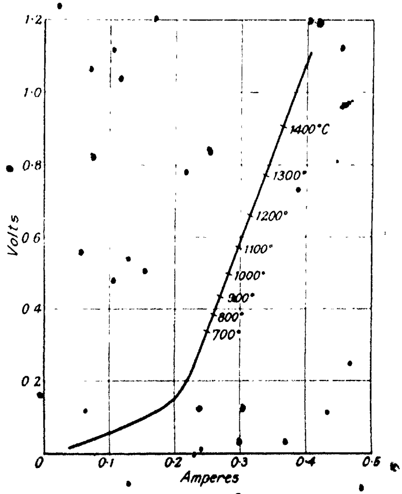

FIG. 35.

CURRENT-VOLTAGE CHARACTERISTIC OF TUNGSTEN FILAMENT LAMP FOR USE IN AN OPTICAL PYROMETER.

In order to estimate the scale law of the arrangement, reference may be made to Fig. 35, which shows the ampere-volt relationship of a tungsten

filament lamp of the type used in these pyrometers. It will be seen that over the range with which we are concerned (700°–1.400° C.) the relationship is approximately linear, so that—

$$E = mC - n,$$

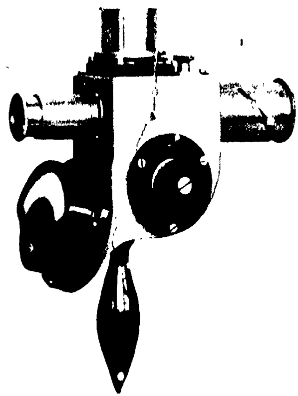

FIG. 56.
OPTICAL PYROMETER MADE BY FOSTER INSTRUMENT CO., WITH INTERCHANGEABLE "LAMP-BRIDGE UNIT."
(See Fig. 34.)

where m and n are constants. This gives the following relation between resistance and current—

$$R = m - \frac{n}{C}.$$

If now the bridge is in balance for a current C_1 and resistance R_1 in the lamp arm, the out-of-balance

deflection for a current C_2 and resistance R_2 will be given by—

$$C_g \propto (R_2 - R_1) C_2$$

$$\propto \left(\frac{1}{C_1} - \frac{1}{C_2}\right) C_2$$

$$\propto (C_2 - C_1).$$

since C_1 is constant.

Hence we get the rather curious result that the scale law for the bridge arrangement is approximately the same as that given by the simple current-temperature relationship.

If each lamp is associated with its own resistances d and b it is obvious that lamps adjusted for the same temperature range will be interchangeable in the bridge. In practice it is convenient to associate the four resistances with the lamp and separate them from the system at the points e, f, h, k, in Fig. 34.

Laboratory Standard Optical Pyrometer.

For work of the highest precision it is necessary to use a more elaborate form of instrument than would suffice for works' use.

The laboratory standard optical pyrometer, shown in Fig. 37, is in use in the Heat Department of the National Physical Laboratory. The design of this instrument is due to F. H. Schofield and Edgar A. Griffiths, and is based on the researches of Forsythe and his collaborators at the Nela Research Laboratory. The instrument is a duplex one, two lamps being fitted which can be readily interchanged by the movement of a lever. Thus check may be maintained over the permanency of the calibrations.

The lamp carriage is so designed that each lamp can be adjusted in three planes without disturbing the other. The range of temperature that can be

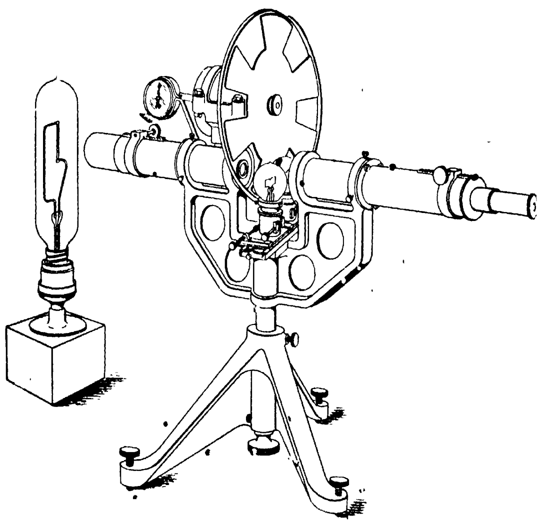

FIG. 37.
LABORATORY STANDARD OPTICAL PYROMETER.

measured in the ordinary way is from 650° to 1,500° C. For measurements beyond this upper limit it is necessary to employ some device for cutting down the intensity of the light from the hot object by a definite amount. The usual practice is to insert

a piece of neutral tinted glass in the path of the beam from the hot object and determine its absorption factor experimentally, but where it is desirable to obtain by calculation the magnitude of this reduction factor, rotating sectors must be used. These are discs of steel with radial slots. The range of temperature available with various sized sectors is illustrated by the following example:

A pyrometer calibrated with full aperture had a scale covering the range up to 1,550° C.; with a $\frac{1}{60}$ sector the range was extended to 2,500° C.; and with a $\frac{1}{180}$ sector the scale was extended to include the melting point of tungsten (3,300° C. approx.).

The difficulty in the use of sectors is that they have to rotate at such a speed that no flicker is noticeable. To accomplish this the alternations must be at least 30 to 40 per second. This is for the condition where the open and closed spaces of the sector are about equal in size. If there is a very great difference between the open and closed parts of the sector, as for instance, in the case of a 2-degree sector with two 1-degree openings, the speed must be higher.

Hence, except for standard laboratory instruments, the use of a rotating sector is not to be recommended, but a piece of neutral-tinted glass calibrated on a standard instrument.

In the case of the instrument illustrated in Fig. 37, sectors about 14 in. in diameter are rotated by a $\frac{1}{4}$ h.p. motor. The sectors are interposed just in front of the lamps as recommended by Forsythe.

Scale Range of Various Sectors. The radial slots in the various sectors of the instrument, shown in Fig. 37, were so planned that the energy transmitted was reduced in the proportions shown in Table V,

which also gives the extension of the temperature scale corresponding to the melting point of palladium (1,828° K.)*—

TABLE V

REDUCTION OF ENERGY TRANSMITTED AND EXTENSION OF SCALE OF OPTICAL PYROMETER BY USE OF SECTORS

No. of Openings.	Total Transmission	Extension of Scale from 1,828° K. for a Wave-length of 0·66μ.
		°K.
2	0·749	1,874
6	0·498	1,941
6	0·247	2,071
6	0·0811	2,317
3	0·0306	2,585
2	0·0163	2,795
2	0·00575	3,227

Pyrometer Lamps.

Either tungsten or carbon filament lamps are suitable for use in optical pyrometers.

Some care is necessary in the process of manufacture when selecting the bulbs. Any striations or defects in the glass which happen to come in the line of sight, will render the lamp of but little use in pyrometry. Troubles with defects in the glass walls become particularly insistent when the highest precision is aimed at in temperature measurements.

The Bureau of Standards has recently succeeded in constructing lamps with optical flats in the bulbs to sight through. A sketch of one type of lamp evolved is shown in Fig. 38. Two optical flats are fused on to the ends of the cylindrical glass tube constituting the lamp bulb, so that the distortion of the image due to inhomogeneity of the glass walls

* K denotes absolute temperatures, i.e. Centigrade + 273.

is eliminated. Such lamps should prove of great service in pyrometry when they become available commercially.

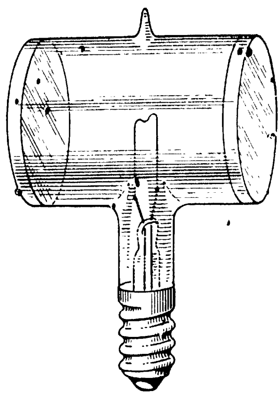

FIG. 38.

PYROMETER LAMP WITH FLATS OF OPTICAL GLASS, DEVELOPED BY DR. FAIRCHILD, OF THE BUREAU OF STANDARDS.

The flats are inclined to the vertical to avoid multiple reflections of the filament.

Calibration of Optical Pyrometers.

The usual procedure is to give optical pyrometers a point by point calibration over the range from about 650° to 1,550° C. A furnace suitable for such calibrations is illustrated in Fig. 39.

For the major portion of the temperature range a thermoelement (calibrated by means of the freezing points of pure metals as described in Chap. III) is

used for determining the temperature of the furnace. This thermoelement is so arranged that its junction is in contact with the surface of the fireclay plug in the centre of the furnace, upon which the pyrometer is sighted.

For the highest point the melting point of palladium, 1,555° C., is observed directly. Since it is only possible to attain temperatures of the order of 1,450° C. in furnaces wound singly with platinum foil, on account of the liability to fuse the platinum, the cascade principle is adopted for the higher temperatures. Two concentric tubes wound with platinum foil are employed.

The external winding brings the temperature of the furnace up to about 1,000° C., whilst the inner winding raises the temperature of the inner tube to 1,550° C.

The "set up" of the furnace for the palladium point is illustrated in Fig. 39. Across the face of the fireclay disc is placed a short length of palladium wire between two platinum leads. The melting of the palladium is indicated by the rupture of the electric circuit. In the experiment the temperature of the furnace is raised at an extremely slow rate and the temperature is observed, at the moment of rupture, on both the optical pyrometer and the thermoelement. The thermoelement then serves for maintaining the temperature of the furnace at this point for further comparisons.

An alternate method is to have two thermocouples, one of which has the hot junction bridged by a short length of palladium. When the furnace is heated up at a steady rate the readings of the two couples keep close together until the melt, when there is a well-defined halt.

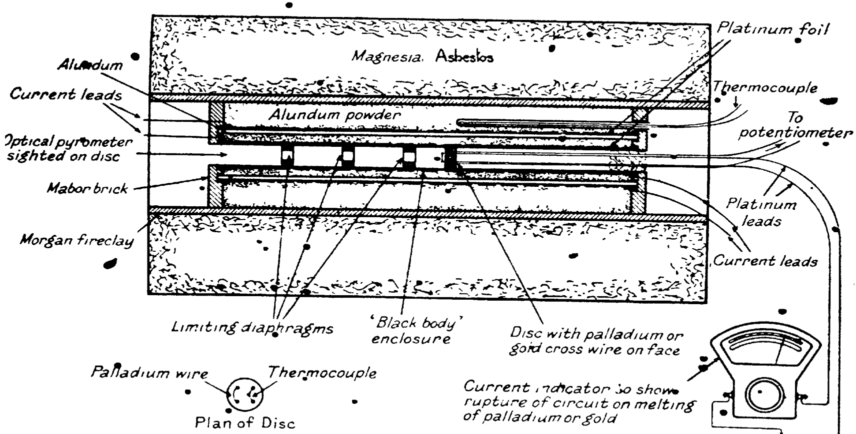

Fig. 39

Furnace for the Calibration of Optical Pyrometers.

Two separate windings of platinum foil are provided to give temperatures up to 1 550° C. The thermocouple connected to the potentiometer is used for maintaining the temperature steady at the point at which the melting of the palladium occurs.

It is also possible to attain these temperatures with the aid of a graphite spiral furnace, heated with alternating current of high amperage and low voltage.

To protect the palladium and platinum from the reducing atmosphere, a porcelain liner tube is employed, as shown in Fig. 40.

Wide Strip Filament Lamp for Intercomparison of Optical Pyrometers.

When a number of pyrometers have to be standardized, the point by point calibration on a "black body" furnace, as described on p. 97, becomes laborious, and an alternative method which is coming into use is to substitute for the furnace a lamp with a heavy tungsten filament, for which the relation between the apparent temperatures corresponding to a series of definite currents has been determined, by the aid of a standard optical pyrometer.

The same method was recently employed in an intercomparison* of temperature scales between the National Physical Laboratory and the Nela Research Laboratory of the General Electric Co., Cleveland, U.S.A.

These intercomparisons were effected through the intermediary of three heavy current lamps, which were especially constructed for the work by the Nela Research Laboratory; some of the lamps had the tungsten strip arranged vertically, others had the strip horizontally. The strips were 1·7 mm. wide in some lamps and 2·5 mm. in others. Each lamp was provided with an index, so as to indicate the particular area on which the observations were to be taken.

* N.P.L. Report, 1922.

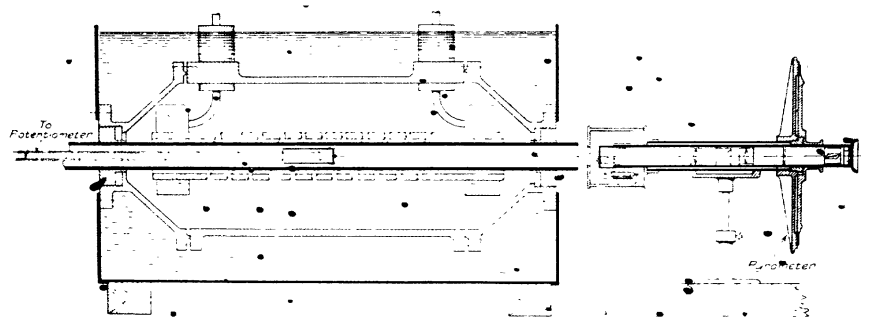

Fig. 40.

Graphite-spiral Furnace for Standardizing Optical Pyrometer Against Thermocouple.

Fig. 37 shows diagrammatically one of the lamps set up in front of the laboratory standard optical pyrometer.

The results of the intercomparisons between the data obtained in the two laboratories are shown in Table VI.

TABLE VI

INTERCOMPARISON OF TEMPERATURE SCALES OF NELA RESEARCH LABORATORY AND THE NATIONAL PHYSICAL LABORATORY

All Values Reduced to a Common Wavelength (0 665μ)

Lamp	Nela, 1920.	National Physical Laboratory (a).	Nela, 1922 (b).	Difference: Col. (b), less Col. (a).
	°K	°K	°K	°K.
T 77B	1,410	1,403	1,406	+ 3
	1,599	1,596	1,595	− 1
	1,796	1,794	1,794	0
	2,106	2,106	2,104	− 2
T 78C	1,825	1,825	1,826	+ 1
	2,262	2,265	2,266	+ 1
	2,746	2,757	2,753	4

REFERENCES -

Fairchild and Hoover: *Jour. Opt. Soc. Amer.* 7 (1913), p. 543. A paper which gives an analysis of the causes of diffraction and reflection effects round the filament of the pyrometer lamp.

CHAPTER VI

TOTAL RADIATION PYROMETERS

INTRODUCTION: Edser's *Heat*, chapter on "Radiation"; Watson's *Textbook of Physics*, p 291; Watson's *Intermediate Physics*, p. 364.

TOTAL radiation pyrometers utilize both the visible and the invisible heat radiation emitted by a hot object. The basic law is a very simple one, namely, that the thermal radiation from a "black" body varies as the fourth power of its absolute temperature.

Féry devised the first practical type of pyrometer operating on this principle.

In the modern form of his instrument a concave mirror of stainless steel concentrates the radiation on to a pair of minute thermocouples connected in series.

The hot junction of each is a semicircular plate. These are placed in close proximity to each other so as to constitute a blackened receiving disc for the radiation.

The couples are connected to a pivoted indicator.

Total radiation pyrometers are applicable over the same range as optical pyrometers, and can also be made to indicate down to 500° C. They require a larger object to sight upon.

Total radiation pyrometer readings are more seriously affected by departure from "black" body conditions than optical pyrometer readings: for the same departure the error is about four times as much.

One advantage possessed by the total radiation, which is the principal reason for its extensive use in the industries, is that it can be made recording.

The calibration of total radiation pyrometers is effected in much the same way as that employed for optical pyrometers.

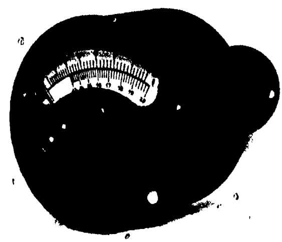

FIG. 41.
TOTAL RADIATION PYROMETER WITH GALVANOMETER BUILT ON TO THE TELESCOPE (SEE ALSO FIGS. 42, 43).

The two commercial forms of total radiation pyrometers in general use in this country are the Féry, made by the Cambridge Instrument Co., and the Foster, made by the Foster Instrument Co.; full details will be found in the lists of these manufacturers.

Total Radiation Pyrometer with Indicator Incorporated in Telescope.

A total radiation pyrometer recently produced has the galvanometer forming an integral part of the telescope. This renders the instrument handy to use as it weighs only $1\frac{1}{2}$ lb. The general appearance

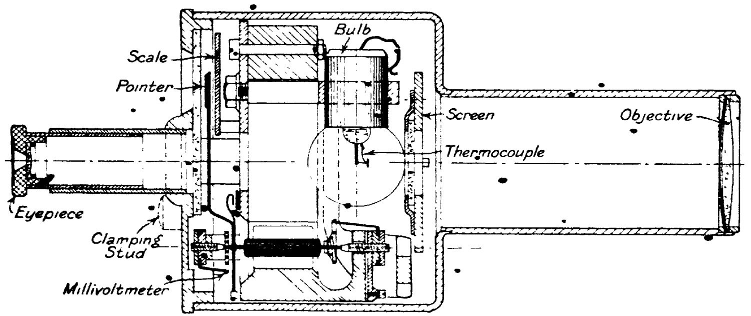

Fig. 42.
Sectional View of Total Radiation Pyrometer Shown in Fig. 41.

of the instrument is shown in Fig. 41, and a sectional view is given in Fig. 42.

The object glass of the telescope is made of a glass of low absorptive power for heat rays. This lens

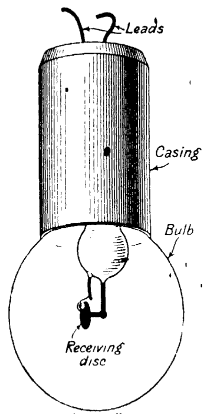

Fig. 43.
Evacuated Bulb with the Absorbing Disc and Thermocouple for the Total Radiation Pyrometer Shown in Fig. 42.

focuses the image of the hot object on to a blackened absorbing disc. To this disc the hot junction of a small thermocouple is soldered and the whole is enclosed in an evacuated glass bulb, as shown in Fig. 43. The two leads from the thermocouple are connected to a sensitive millivoltmeter.

By the aid of suitably placed diaphragms the instrument is self-focusing, and all the observer has to do is to ascertain that the distance between the pyrometer and the aperture sighted through is within the limits demanded by the geometry of the system. The appearance of the field viewed in the telescope indicates whether the distance away from the hot object is less than the prescribed limit.

For an actual temperature measurement, the observer holds the pyrometer to his eye and sights on the object, he then presses the button which releases the moving coil system of the indicator. The needle within a few seconds takes up a position corresponding to the temperature. By releasing the button the needle is clamped in this position, so that the temperature can be read when the observer lowers the instrument from his eye.

Relation between Thermoelement E.M.F. and Temperature of Sighted Object.

When a glass plate is interposed in the beam of radiation received by a pyrometer of the "total radiation" type, the "law" of the instrument is no longer that of the fourth power of the absolute temperature.

Glass absorbs the radiation in both the infra-red and the ultra-violet. Speaking generally, crown glass would cut off practically all the infra-red of wavelength greater than $2{\cdot}5\mu$, and in the ultra-violet all wavelengths shorter than $0{\cdot}35\mu$.

Consequently, we find that the "law" of an instrument, with a glass front or lens, may be nearly that of the fifth power of the temperature, the actual value of the index varying at different parts of the temperature range.

CHAPTER VII

ELECTRIC FURNACES

INTRODUCTION: Moffett's *Electric Furnace* (Pitman, 2s. 6d. net).

IN this chapter it is proposed to give a sketch of typical furnaces which have been employed in recent investigations. It is assumed that the reader is familiar with the nichrome-wound furnaces obtainable commercially, by means of which temperatures up to about 1,000° C. may be obtained.

Molybdenum Wire Wound Furnace.

The high melting points of tungsten and molybdenum (about 3,300° and 2,450° C. respectively) suggest the use of these metals as resistor windings for high-temperature furnaces. Owing, however, to the ease with which they form oxides at high temperatures, it is necessary to operate them in a reducing atmosphere of hydrogen, or of nitrogen mixed with about 5 per cent of hydrogen.

A typical example of a molybdenum furnace is shown in Fig. 44. This furnace was employed by Fieldner and Hall in their study of the fusibility of coal ash in various atmospheres.

The wire is wound on a grooved tube of alundum, and when winding such a furnace it is necessary to heat the wire to a dull red heat whilst it is being coiled on the tube, otherwise it splits up into fibres.

Dantsizen has given the following data concerning molybdenum for the guidance of those desiring to construct furnaces with this metal. He states that

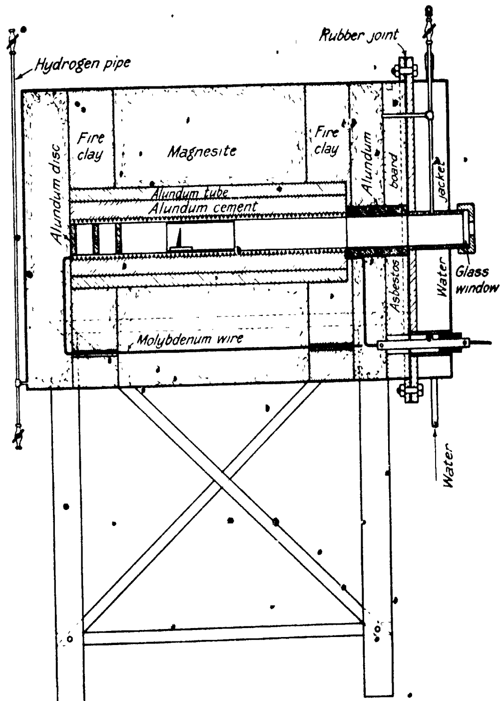

FIG. 44.
MOLYBDENUM-WOUND FURNACE FOR DETERMINING FUSIBILITY OF COAL ASH.

the specific resistance of molybdenum at 0° C. is 4·1 microhms per cm.-cube, and that the temperature coefficient is 0·005 per °C. Hence a wire at 1,700° C. has about 8·5 times its resistance at room temperature.

As a rough rule in the design of a furnace, 6 watts per sq. cm. of heating surface should be allowed, in order to maintain a temperature of 1,700° C.

The winding should be arranged to keep the potential drop less than 1 volt per 2·5 mm. between the turns. For example, if two adjacent turns of a winding are 7·5 mm. apart, a potential drop of more than 3 volts in a single turn might lead to breakdown in the insulation of the alundum tube at high temperatures, and the arcing produced would soon burn out the winding.

Furnaces for Testing Refractories.*

An important application of electric furnaces is in determining the softening points and compressive strengths of refractory materials at high temperatures. For this purpose furnaces capable of attaining temperatures up to 1,800° C. and over are necessary. The furnace illustrated in Fig. 45 was devised by Mr. Edgar A. Griffiths and the writer for testing refractories.

This furnace is of the carbon tube type contained within a sheet-iron casing, 12 in. in diameter by about 12 in. in length. The two ends are made of asbestos composition material, so as to obtain electrical insulation for the electrodes, etc. The

* These notes, from p. 108 to 121 inclusive, are reproduced by permission, with revision and additions where necessary, from the author's article on "Electric Furnaces," in the *Beama Journal*, Vol. IX, 1921.

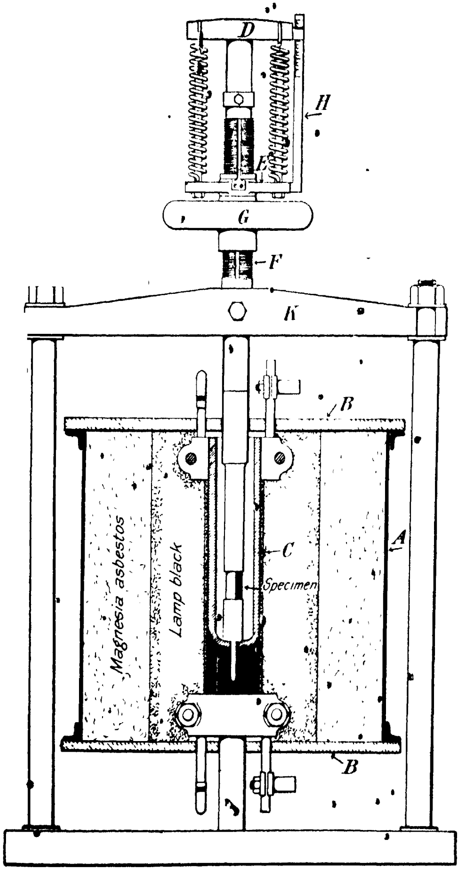

Fig. 45.
Carbon Tube Furnace for Testing Refractories Under Load.

carbon tube C is 2 in. outside diameter and $1\frac{1}{2}$ in. inside diameter, and, to admit of temperature observations on the specimen, a $\frac{1}{4}$ in. slot is cut nearly the whole length of the tube. The reason for making a slot and not a round hole is to obtain uniformity in the resistance of the tube throughout its length. Around the tube is packed a thick layer of lamp black and outside this a layer of magnesia asbestos lagging. In the construction of the electrodes two copper tubes were bent into a zigzag form and white metal cast around the tubes, the mould being formed of strip iron with a piece of the carbon tube as core. Each electrode was cast in two halves and with care the casting obtained would fit the carbon tube exactly, so there was no need for machining the metal faces.

The specimen of refractory material is tested in the shape of a cylindrical block, about 1 in. in length and $\frac{1}{2}$ in. in diameter. This is placed between two carbon rods and pressure applied by the arrangement shown in Fig. 45. The magnitude of the pressure, which is adjustable up to 150 lb. per sq. in., is measured on the scale H, while the whole arrangement is carried on the cross bar K, which can be swung around one of the furnace pillars in order to obtain access to the furnace interior.

Arc Furnaces.

The earliest record we have of arc furnaces being used on a large scale for metallurgical experiments, is that of Siemens in 1880; later of Siemens and Huntington, when they melted 20 lb. of steel in one experiment and 8 lb. of platinum in another.

The subject was taken up later by Moissan, who started out with the object of manufacturing

artificial diamonds. His work, however, contributed largely to our knowledge of carbides and of the chemistry of materials at high temperatures.

The form of arc furnace employed by Moissan is extremely simple and is illustrated in Fig. 46. Two blocks of limestone *A* and *B* are hollowed out. The lower block contains the crucible which is made of carbon. The arc plays between the carbon electrodes and the heating is effected by radiation from the surface of the cavity in the upper block. The

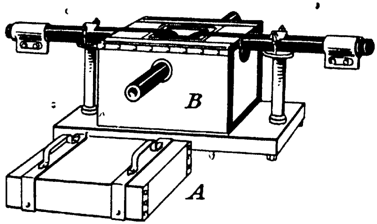

FIG. 46.
MOISSAN'S ARC FURNACE

difficulty is to obtain any material to stand the temperatures; lime, quartz, and alumina melt and boil at the temperature attained.

Induction Furnaces.

The induction furnace is practically a transformer with a secondary of a single turn, this being in general a bath of molten metal.

The idea of a furnace on this principle appears to be due to Ferranti, while considerable developments of this type were made by Kjellin. The

fundamental principle of the furnace is illustrated by Fig. 47.

A primary P is wound around the central limb of the laminated iron transformer, of which one side is removable. This primary is composed of copper tubing through which a stream of water is circulated. The secondary S consists of an annular trough containing the metal charge in the form of a continuous ring.

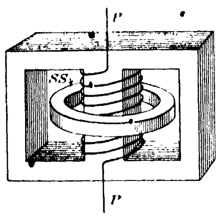

FIG. 47.
DIAGRAMMATIC REPRESENTATION OF THE INDUCTION FURNACE.

The advantages possessed by a furnace of this type are that there are no electrodes to contaminate the charge; the heat is uniformly generated in the material; and there is also no danger of contamination by furnace gases. In this last respect the furnace is superior even to a closed crucible, since it is impossible in practice to avoid some furnace gas entering a crucible in an ordinary furnace.

The induction furnace finds its chief application commercially in the manufacture of high-class tool steel of a definite composition. The primary can be designed to take any voltage and values as high as 6,000 volts have been employed. The disadvantage of the furnace is that the annular channel has to be very long compared with its cross-sectional area in order to obtain sufficient electrical resistance, and consequently there is loss of heat by radiation and convection. It is also necessary to provide an

air space between the primary and secondary, and in consequence the furnace does not form a very effective transformer, the power factor becoming smaller as the furnace becomes larger unless the frequency of the current is correspondingly reduced. This necessitates a generator of low periodicity.

High-frequency Induction Furnaces.

Dr. Northrup has developed a new form of furnace based on the induction principle.

The ordinary induction furnace, operating on commercial supply frequencies, consists essentially of a step-down transformer, the secondary being a closed loop of one turn. This single turn is usually molten metal contained in an annular trough of refractory material, through which is looped the iron core of the transformer.

Northrup showed that by employing current of high frequency the use of the iron core becomes unnecessary, and all that is required is that the primary winding should encircle the crucible of metal to be heated. With a frequency of 20,000 cycles per second, the powerful inductive effect causes a rapid rise of temperature in the material. For furnaces under 100 kW. capacity the source of high-frequency current is the oscillatory discharge of a bank of condensers. By properly proportioning the capacity and inductances of the oscillatory current circuits, the desired frequency is readily obtained and the electrical connections for single phase operation are shown in Fig. 48.

The line current may be supplied at any pressure from 100 to 500 volts and at about 60 cycles frequency. The transformer steps up the E.M.F. to 8,000 volts. A bank of condensers is charged at

this voltage and upon rupture of the gap oscillations occur.

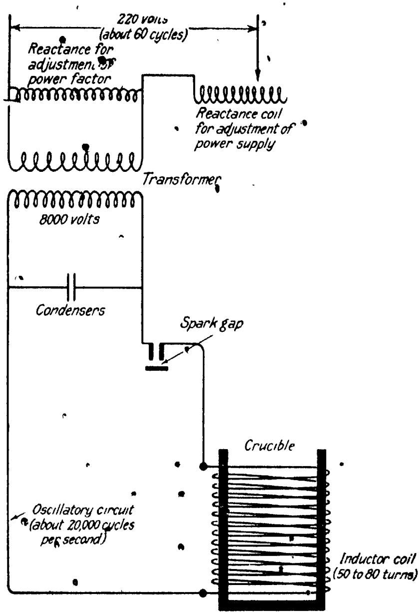

FIG. 48.
ELECTRICAL CIRCUITS OF THE NORTHRUP HIGH-FREQUENCY INDUCTION FURNACE.

The current with free high-frequency oscillations passes through an "inductor" coil which surrounds

the crucible or mass to be heated. When non-conducting materials are to be heated, the crucible itself is made of electrical conducting material and the heat generated in this.

The control over the heating is obtained by means of the reactance coil shown. The other reactance, connected in shunt to the line on the primary side of the transformer, serves to adjust the power factor of the line to practical unity.

The power which the furnace will absorb is exactly proportional to the number of condenser units employed, and calculation and experiments show that for a condenser unit 12 × 16 × 13 in., of capacity 0·07 microfarad, 1·5 kW. per unit can easily be obtained. About sixteen condensers would be required for a 20 kW. furnace outfit. It is stated that not less than 50 to 60 per cent of the power drawn from the mains appears as heat in the crucible and its contents.

The discharge gap is an essential element of the outfit and exhibits some novel features. It has no moving parts and consists of two graphite electrodes (three for two-phase or three-phase operation) opposed to a level surface of mercury. The mercury is contained in a cast-iron pot and the level of the mercury is made adjustable from without. The electrodes with graphite tips project through the cover, which is made closely fitting so as to minimize noise. The gap is found to operate better, and the surface of the mercury to keep cleaner, if alcohol is dropped into the chamber at about fifteen drops a minute.

It is stated that, eventually, with the further development of the Alexanderson high-frequency alternator, this discharge gap will be dispensed with,

since with this type of generator it is believed that efficiencies as high as 90 to 93 per cent can be obtained.

As to the possibilities of the furnace, it is stated that nickel (melting point 1,452° C.) can readily be fused.

One of the proposed large-scale adaptations of this furnace is for the retention of the heat in the steel ladle. In this case the inductor coil would be embedded in the refractory lining of the ladle.

The high-frequency induction furnace has been used for heating roller-bearing rings before hardening, the desired quenching temperature being reached in a very few minutes. No crucible was required, the energy being generated directly in the rings.

For scientific purposes the furnace promises to be of utility, for by its aid refractory alloys can be prepared without the danger of contamination from carbon, as is the case with carbon tube or arc furnaces.

Northrup states that tests have shown that a uniform temperature of 1,600° C. can be obtained throughout the volume of a cylinder 6 in. in diameter and 12 in. long, with a 20 kW. outfit.

Vacuum Cathode Ray Furnaces.

Wartenberg* has constructed a special vacuum furnace for determining the melting point of tungsten. As this melting point is above 3,000° C., the only resistance material that came into consideration was carbon which, however, could not be used because tungsten reacts chemically with the gases

* *Berichte der Deutschen Chem. Ges.*, Vol. 40, 1907. See also Parsons and Swinton *Proc. Roy. Soc.*, A., 184. 1908.

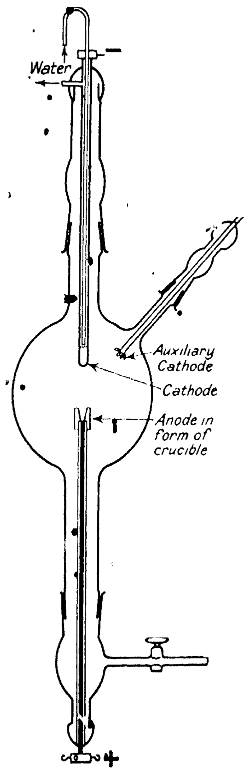

FIG. 49.
FISCHER'S CATHODE-RAY FURNACE.

developed by the glowing carbon. Wartenberg solved the problem by using the heating effect on the anode of the discharge in a Geissler tube. As the evacuated tube has a high resistance and a strong current is necessary to give the required heat to the anode, a Wehnelt cathode is employed to supply the electrons. This cathode consists of a platinum sheet heated electrically to white heat, when it emits a copious stream of electrons. The action is considerably increased, if the platinum is covered with lime, by repeated painting with calcium nitrate solution and heated to redness. Generally the strip of platinum sheet (1 cm. wide 6 cm. long, and 0·04 mm. thick), is fastened between two small copper tubes, which conduct the current and are water-cooled. The strip is heated by an alternating current of 25 amp. and 2·5 volts to about 1,300° C. At this temperature 2 to 3 amp. per sq. cm. of cathode surface may be sent through the vacuum tube. For this particular case the current is 24 to 36 amp. The anode consists of a 4 mm. diameter iron wire (iron is chosen because it is comparatively a bad conductor of heat), which is insulated almost to its extreme end by a glass tube drawn over it, and on which a magnesia tube is cemented with water glass. The compressed stick of the tungsten to be melted is placed in this tube.

In order that the furnace may be taken to pieces easily the copper pipes and the iron wire are not cemented into the glass tube forming the furnace jacket, but into the removable stoppers (which are covered inside with water-glass magnesia cement and outside with sealing wax). To start the furnace the air is pumped out to 0·01 mm. pressure, the cathode is heated to white heat by means of a

current from the transformer, and then the main current from the 110 volts direct current circuit is gradually increased until it reaches 20 amp. The fall of potential of about 40 volts inside the tube is concentrated almost entirely on the anode, so that here a considerable amount of energy (about 800 watts), is transformed into heat within a very small space and rapidly melts the tungsten which may be raised even to its boiling point. In order to observe the melting, a glass observation window is cemented into the narrow end of the tube with marine glue.

Fischer* has modified this furnace into a form resembling an X-ray bulb (Fig. 49). A three-litre glass sphere with three openings serves as a vessel, and in the three openings three electrode holders are inserted. The lower holder contains the tungsten as anode, the upper holder in like manner the tungsten cathode. The latter plays the part of the Wehnelt cathode and for this purpose is covered with calcium and barium oxide. Both electrode holders are cooled with water. Through the side tube a small auxiliary cathode is introduced, also of tungsten. The conductors leading to the tungsten poles are carefully insulated from the glass by quartz magnesia tubes and cemented in with sealing wax.

In later experiments Fischer built a similar furnace of pure copper of 20 litres capacity, in which the anode and cathode were horizontal and the auxiliary cathode vertical.

* *Zeitschrift f. Anorg. Chem.* Vol. 81, p. 178, 1913.

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The undermentioned Technical Primers (Pitman, 2s. 6d. net), are likely to interest readers of this book

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